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THESIS

AN ANALYSIS OF OPERATIONAL AVAILABILITY OF BRAZILIAN NAVY AND ARGENTINE AIR FORCE A-4 FLEETS USING SIMULATION MODELING

by

Marcelo B. Rodrigues

Mario Karpowicz

December 1999

Thesis Advisor: Keebom Kang
Associate Advisor: Donald R. Eaton

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This thesis analyzes the impact of reducing transportation cycle time and consolidating aviation electronic component inventory management on the operational availability of the Brazilian Navy and Argentine Air Force A-4 fleets. The research is based on a scenario where the Brazilian Navy operates twenty A-4 aircraft, while the Argentine Air Force operates thirty A-4s, and both countries rely on manufacturers in the United States for depot-level maintenance. The transportation turn-around-time is extremely long and the cost of some inventory items is very high. A simulation model was developed representing the repair process of a selected group of A-4 critical electronic components. This particular model provides an effective managerial resource for long-term decision making to improve the readiness of aircraft fleet for both countries. We also developed a multiple regression analysis model (metamodel) to find the relationship between spare inventory levels and the operational availability. These results were applied to a linear programming model to find optimal spare levels for these critical components by minimizing the total cost while maintaining the desirable military readiness. Through a cost-effectiveness analysis, we compared the two situations, optimal spare levels with reduced transportation time and actual spare level with current transportation time. Our research concludes that both Armed Forces will improve readiness, while achieving significant savings, if they reduce the transportation time for the aviation electronic components sent to the United States for depot-level maintenance, and collaborate on the inventory management of their A-4 fleets.

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Marcelo B. Rodrigues
Lieutenant Commander, Brazilian Navy
B.S., Brazilian Naval Academy, 1983

and

Mario Karpowicz
Major, Argentine Air Force
B.S., Escuela de Ingeniería Aeronáutica, 1982

Submitted in partial fulfillment of the
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NAVAL POSTGRADUATE SCHOOL
December 1999

Author: ______________________
Marcelo B. Rodrigues

Author: ______________________
Mario Karpowicz

Approved by: ______________________
Keebom Kang, Thesis Advisor

____
Donald R. Eaton, Associate Advisor

____
Reuben T. Harris, Chair
Department of Systems Management

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ABSTRACT

This thesis analyzes the impact of reducing transportation cycle time and consolidating aviation electronic component inventory management on the operational availability of the Brazilian Navy and Argentine Air Force A-4 fleets. The research is based on a scenario where the Brazilian Navy operates twenty A-4 aircraft, while the Argentine Air Force operates thirty A-4s, and both countries rely on manufacturers in the United States for depot-level maintenance. The transportation turn-around-time is extremely long and the cost of some inventory items is very high. A simulation model was developed representing the repair process of a selected group of A-4 critical electronic components. This particular model provides an effective managerial resource for long-term decision making to improve the readiness of aircraft fleet for both countries. We also developed a multiple regression analysis model (metamodel) to find the relationship between spare inventory levels and the operational availability. These results were applied to a linear programming model to find optimal spare levels for these critical components by minimizing the total cost while maintaining the desirable military readiness. Through a cost-effectiveness analysis, we compared the two situations, optimal spare levels with reduced transportation time and actual spare level with current transportation time. Our research concludes that both Armed Forces will improve readiness, while achieving significant savings, if they reduce the transportation time for the aviation electronic components sent to the United States for depot-level maintenance, and collaborate on the inventory management of their A-4 fleets.

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I. INTRODUCTION

A. BACKGROUND

The year of 1998 has a special meaning in the military arena for two South American countries. In that year, the Argentine Air Force and the Brazilian Navy added power to their fleets with the incorporation of the Douglas A-4 Skyhawk aircraft. On the other hand, this event represented the need to build a new infrastructure from a maintenance point of view. However, this is a task that cannot be accomplished in the short term, especially for two Armed Forces that are under great pressure to reduce military infrastructure costs and lower workforce levels due to the economic recession in both countries. Since Argentina and Brazil have limited capability to repair complex avionic electronic components, they must rely on manufacturers in the United States for depot level maintenance.

Greater reliance on sophisticated avionics, reductions in the defense budget and lower workforce levels form a precarious combination that both the Argentine Air Force and the Brazilian Navy must contend with now and in the future. This combination requires that both Armed Forces repairable-item inventory systems operate in a highly efficient manner with regards to their logistical structures, managerial decisions, and budgetary constraints. An effective repairable-item inventory system must not only provide them with the ability to maintain the desired level of combat readiness, but must do so at an affordable cost.

Similarities like the ones previous mentioned have provided a favorable scenario for the development of joint solutions between Argentina and Brazil. In fact, the pattern of many recent actions has shown that a strong integration process is already in place, and any initiative heading towards this direction is very welcome.

B. PURPOSE

In response to the common needs of both the Argentine Air Force and the Brazilian Navy concerning the acquisition of the A-4 aircraft, this thesis presents a collaborative solution which provides an effective managerial resource to support inventory and transportation logistics decisions in the inventory management of their A-4 fleet aircraft maintenance.

The scope of the developed model is broad, and it does not intend to be a solution for a single case, but to provide the logistics decision makers with a decision support tool for analyzing the operational availability of their fleets and their related repairable-item inventory system.

C. RESEARCH QUESTIONS

The following is a list of primary research questions that are addressed by this thesis:

- Can the Argentine Air Force and the Brazilian Navy eliminate inappropriate investments in excessive inventory levels of Line-Replaceable Units (LRUs) while increasing operational availability of the A-4 aircraft?

- Is a consolidated inventory control point for critical LRUs a feasible solution for the Argentine Air Force and the Brazilian Navy? What is the value added for establishing a consolidated inventory control point for both armed forces?

- What are the main effects of reducing transportation cycle time? What mode should be used for shipping the items in the reparable-item inventory system?

D. METHODOLOGY

Extensive archival research was done through books, research papers, and newspaper and Internet articles. We also examined military literature and performed a review on selected issues concerning Latin American security. The latter was fundamental to show evidence regarding the positive and receptive environment that currently exists for joint efforts among Latin American countries, and more specifically between Brazil and Argentina.

Telephone interviews were also conducted with personnel from the Argentine Air Force and the Brazilian Navy, and relevant data was collected trough e-mails. We visited the Argentine A-4 Aircraft Program representative office in Palm Dale, California where A-4 avionic components data was gathered. In order to better understand the operations of a depot level maintenance facility, we conducted personal interviews during an on-site visit to the United States Naval Aviation Depot–North Island in San Diego, California. Key personnel involved in those interviews were the Fleet Support Team Leader [Ref. 1], engineers and some logisticians.

With all information in hand, we used a simulation software package (Arena) to develop a model representing the repair process of a selected group of A-4 critical electronic components. This particular model is an effective tool for long-term decision making to improve readiness for both countries. We also developed a multiple regression analysis model (metamodel) to find the relationship between spare inventory levels and

the operational availability. These results were applied to a linear programming model to find optimal spare levels for these critical components by minimizing the total cost while maintaining the desirable military readiness. Ultimately, we compared the current scenario to a proposed one in order to show the results of a reduction in inventories and transportation cycle time on a consolidated model. In addition to Arena, other software such as Microsoft Excel, QM for Windows, and Crystal Ball were fundamental in achieving results for this thesis.

E. ORGANIZATION OF STUDY

Chapter II provides a review of Argentine-Brazilian relations. It shows that consolidation of efforts and joint trading are goals that Argentina and Brazil are pursuing. Chapter III discusses the similarities and differences between the two A-4 Aircraft Repairable-Item Inventory Systems. To provide the reader with background information about technical expressions and meanings, we dedicated part of this chapter to the definition of essential terms. Chapter IV presents all the information about the development of our simulation model. Simulation assumptions and model descriptions are included here. With the complete model from Chapter IV, Chapter V discusses running the simulation model as a coalition model, where we propose consolidating aviation electronic component inventory management for the Brazilian Navy and the Argentine Air Force A-4 fleets. Chapter VI suggests a reduction in transportation cycle time for the coalition model. Effects on operational availability for both countries are covered. Chapter VII delineates the multiple regression analysis model (metamodel) used to guide the sensitive analysis performed on the following chapter. With the metamodel

provided from Chapter VII, we populated Chapter VIII with valuable information for the decision makers. First, informative graphics were added in order to provide illustrative analysis for the dilemma "number of spares vs. operational availability." Then, a linear programming concept is reviewed and applied on a cost minimization problem. Chapter IX provides cost-effectiveness analysis where the current scenario is compared to a proposed one. The final chapter, Chapter X, presents conclusions and recommendations.

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II. ARGENTINE-BRAZILIAN RELATIONS

A. CHAPTER OVERVIEW

Argentina and Brazil have an interesting bilateral cooperation history, especially in economic and military issues. Since 1979, when their respective military regimes resolved the hydroelectric conflict concerning Paraguay and the use of the Parana River waters (the building of the Itaipu dam), an escalation of efforts and decisions have been successfully developed and implemented towards the stabilization of the economic cooperation and integration process. [Ref. 2]

This chapter presents a brief overview of the relevant aspects involved in Argentine-Brazilian relations that guarantee a very positive and receptive environment to embrace the core idea of inventory consolidation embedded in this research paper.

B. ECONOMIC COOPERATION

> On 30 November 1985 Presidents Alfonsin (Argentina) and Sarney (Brazil) met at Foz do Iguaçu to inaugurate a programme that took a concrete form on July 31, 1986, with the signing of the Argentine-Brazilian Integration Act and the Integration and Cooperation Program (ABEIP), together with 12 protocols for cooperation in various areas. The ABEIP represented a breakthrough in their bilateral relations, after a century-long struggle for subparamountcy in South America. Its significance was primarily political, not economic: setting aside decades of rivalries and competition in order to create the basis for a long-term cooperation. [Ref. 2]

To supplement and improve their former agreements, Brazil and Argentina signed a Treaty for Integration, Cooperation and Development in 1988 that set the stage for a common market between the two countries with the gradual elimination of all tariff barriers and harmonization of the macro-economic policies of both nations within the

timeframe of ten years. It was further established that this agreement would be open to all other Latin American countries. After the addition of Paraguay and Uruguay a new treaty was signed by all four countries on March 26, 1991 in Asunción, Paraguay which provided for the creation of a common market among the four participants to be known as the Southern Common Market (Mercosur). Chile later joined the Mercosur.

C. EDUCATIONAL INTEGRATION

Based on the premise that education is a fundamental factor in the regional integration process, educational courses at the primary or junior high level--provided that they do not entail technical studies-- will be recognized by member states as being on the same level for all member nations.

Likewise, in order to permit continuing education, certificates proving course conclusion issued by an official institution accredited in one of the member states will be valid in all other member states.

Non-technical primary and junior high level studies that have not been completed will be accredited by any member state, thereby allowing course conclusion in another member nation. Studies will be completed using an equivalency table to determine the level achieved. [Ref. 3]

In August 1998 the Brazilian Senate unanimously voted to make Spanish a mandatory subject for the 6.5 million secondary students in Brazil. Meanwhile, there is a similar plan for Argentina. In spite of its enormous financial difficulties, the Argentine educational system has more than 8,200 professors to be selected to teach Portuguese. For the year 2000, many of the 6000 secondary schools of Argentina, especially in the provinces of the Northeast, will begin to teach Portuguese. [Ref. 4]

D. MILITARY COOPERATION

The process of economic integration of the Mercosur generated a political approach that deactivated any hypothesis of armed conflicts between Argentina and Brazil. The military participation in this process of integration was considered as essential for both governments. An example of military participation occurred when the four Brazilian and three Argentine military ministers were brought together for the first time at the 1985 Foz Iguacu summit. At that time, they established the basis for subsequent negotiations.

In 1986, an integration pact initiated cooperative ventures in the defense industry, including joint production, technical data sharing, and reciprocal subcontracting in the joint development and production of a tactical transport aircraft, the CBA-123. Beyond commercial gains, policy makers sought through this project to create a web of interrelated defense interests and to symbolize the end of military rivalry [Ref 5]. In April 1987, the Sarney and Alfonsin governments initiated annual symposiums of their respective joint chiefs of staff of the armed forces to facilitate communication and overcome history by reciprocal threat scenarios. While restricted in scope, military cooperation served as "one of the guarantees of the process of integration, because it is the most appropriate road to commit the Brazilian and Argentine armed forces, through mutual understanding to democracy" [Refs. 6 and 7]

In the middle of the decade of the 1980s, the Brazilian Armed Forces decided to abandon the concept of Argentina and Brazil being strategic enemies destined therefore to be continuously preparing to be at war. As a result of this change, the Brazilian Army units that were deployed on the border with Argentina were transferred to the Amazon.

Nowadays, the defense of the Amazon is the main concern of the Brazilian national defense.

In April 1997, President Carlos Menem and his Brazilian counterpart Fernando Henrique Cardoso signed an agreement that declares a "strategic alliance" between both countries to assure a common framework for regional security. In order to give impetus to this strategic alliance, the presidents established the "mechanism of consultation and coordination in defense and international security matters" that began to work for the first time in Rio de Janeiro in August of 1997.

With this approach between their militaries, Argentina and Brazil have been looking to fortify the Mercosur politically . The idea is to generate new signals of mutual confidence, such as more joint military maneuvers, interchange of information, cooperation in peace missions, common positions in the international forums, between both countries. An example of this took place in October 1997 when joint military maneuvers took place in Corrientes, one of the northeastern states of Argentina, between both the Argentine and the Brazilian Armies. Later, in December 1997, joint military maneuvers between both Navies took place in the Atlantic Ocean (ARAEx operation), at almost 150 kilometers from the Bahia Blanca coast in Argentina. Brazil participated with its aircraft carrier "Minas Gerais", and Argentina with its naval aviation. The military drills were done under joint Brazilian-Argentine command.

E. THE FUTURE

The future of Argentine-Brazilian relations are summarized in the following public expression from the highest authorities of both countries:

> In 1997, in Rio de Janeiro, president Menem and I registered the mutual disposition to build a Strategic Alliance between Brazil and Argentina.

> We will not move away from this intention. The Mercosur is our most important project of external policy. Its economic-commercial dimension became essential for the progress of our countries. But we also valorize the Mercosur by its political dimension of long term. By keeping and deepening this course of integration, we will guarantee a better insertion in the international system for us and our children. [Fernando Henrique Cardoso, President of Brazil; [Ref. 8]

The recently elected President of Argentina, Fernando De la Rua, publicly expressed last November 4th, on his first visit to Brasilia, the willingness to strengthen the Mercosur and the South Atlantic Defense. In addition, he and the Brazilian President announced the idea of developing joint Argentine-Brazilian Consulates that will start being implemented in South East Asia at the beginning of next year. This idea, once implemented, not only will result in economic benefits for both countries but also will promote the Mercosur among the international community. [Ref. 9]

F. CHAPTER SUMMARY

This chapter showed the strong process of integration between Brazil and Argentina. This integration covers not only economic subjects such as a common economic market, but also it includes educational and military cooperation among others. This close relationship is being reinforced by the concrete actions taken by the authorities of both countries at present and envisioning the future.

The integration provides a strong argument in developing the idea of military inventory consolidation such as the one that in particular is developed in this paper for the A-4 aircraft fleets of the Brazilian Navy and the Argentine Air Force. The benefits of close cooperation and sharing of resources between the two countries are the core of this paper.

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III. CHARACTERISTICS OF THE ARGENTINA AND BRAZIL'S REPAIRABLE-ITEM INVENTORY SYSTEMS

A. CHAPTER OVERVIEW

The purpose of this chapter is to provide an understanding of a military repairable-item inventory system, and make the reader familiar with the similarities and differences between the Argentina and Brazilian systems. However, it seems appropriate to direct some attention to the terminology before proceeding. Thus, a few terms and definitions are discussed to provide the reader with the fundamentals needed to better understand the material presented in this chapter.

B. MILITARY REPAIRABLE-ITEM INVENTORY SYSTEMS

1. System Description

A repairable-item inventory system is used for controlling items that are generally very expensive and have long acquisition lead times. A standard military repairable-item inventory system consists of a repair facility (depot) dedicated to support one or more locations (bases) where equipment (aircraft) is assigned. Over time, equipment malfunctions occur due to the failure of a specific item (avionics) internal to the equipment. A corresponding serviceable item is then obtained from an inventory location (rotable pool) and installed on the malfunctioning equipment, thereby restoring it to full operational capability. The failed item is tracked as it is shipped to the repair facility,

scheduled for repair, and subsequently shipped in a serviceable condition back to the original rotable pool.

2. Definitions of Essential Terms

a. LRU (Line-Replaceable Unit)

A line-replaceable unit is one avionics subassembly considered essential for the Douglas A-4 Skyhawk aircraft to perform its primary flying mission. Examples of LRUs are digital mission computers, radar altimeters and so on.

b. SRU (Shop-Replaceable Unit)

Each LRU contains subcomponents which are defined as shop-replaceable units. Examples of SRUs include circuit cards, high voltage power supplies and so on.

c. Rotable Pool

A rotable pool (RP) is a stockpile of spare parts, either LRUs or SRUs, that provides a spare in serviceable condition to facilitate a quick repair of a faulty component. Therefore, whenever there is a faulty component it can be quickly repaired and installed in the aircraft without waiting for the actual faulty LRU/SRU to be repaired.

d. Operational Availability

Operational Availability, commonly referred to as "A_0", is the key performance parameter of a logistics support system. Here is Blanchard's definition of A_0:

> *Operational availability* is the probability that a system or equipment, when used under stated conditions in an *actual* operational environment, will operate satisfactorily when called upon. [Ref. 10:p. 81]

The following equation shows how A_0 is expressed.

$$A_0 = MTBM / (MTBM + MDT)$$

MTBM is the mean time between maintenance and MDT is the maintenance downtime [Ref. 10:p. 81]. Therefore, we can see a direct relation showing that whenever the MDT becomes less, A*o* becomes greater. Note that MDT constitutes the total elapsed time required to repair and restore an equipment/system to full operating status, thus including mean active maintenance time, logistics delay time, and administrative delay time [Ref. 10:p. 58].

e. Levels of Maintenance

"Maintenance level pertains to the division of functions and tasks for each area where maintenance is performed." [Ref. 10:p. 116]

According to Blanchard [Ref. 10], there may be two, three, or even four levels of maintenance depending on the nature and mission of the system. This study is focused on a three-level maintenance concept, in which maintenance may be classified as *organizational*, *intermediate*, and *depot*.

Organizational level maintenance, or O-level maintenance, is performed at the operational site (squadron). Basically, it involves tasks related to the support of its own operation, and the removed components are normally forwarded to the intermediate level.

At the Intermediate level maintenance, or I-level maintenance, end items may be repaired by the removal and replacement of major modules, assemblies or piece parts. For instance, this is the kind of maintenance performed by Aircraft Intermediate

Maintenance Departments ashore in either naval air stations (Navy) or bases (Air Force), or afloat in aircraft carriers (Navy).

Finally, the Depot level maintenance, or D-level maintenance, constitutes the highest type of maintenance. Also called supplier or manufactures maintenance, this level of maintenance supports O- and I-level activities. Thus, tasks accomplished here included performing maintenance beyond the capabilities of maintenance (BCM) of those two previous levels. The depot facilities are generally remotely located to support specific geographical area needs or designated product lines.

C. ARGENTINA AND BRAZIL'S A-4 AIRCRAFT REPAIRABLE-ITEM INVENTORY SYSTEMS

The existing systems in both countries have many similar characteristics. They are mainly based on the system used in the United States Navy. Basically, when a repairable item fails, a corresponding serviceable item is obtained from an inventory location at the base and installed on the aircraft; thereby restoring it to fully mission capability. Some of the repairable items can be repaired in Brazil and Argentina depending on the maintenance level required. We can assume the same three levels of maintenance previously mentioned for Brazil's and Argentina's A-4 aircraft maintenance programs. At present, the Depot-level maintenance for the LRUs/SRUs considered in this thesis takes place in the United States. The cycle time from the moment that a failure is detected until the moment when the item returns to the base in a serviceable condition is anywhere from three to six months. The long turnaround times adversely affect the readiness of A-4 squadrons.

1. Argentine A-4 Aircraft Repairable-Item Inventory System

Due to the technological complexity of its A-4 aircraft upgraded version, the Argentine Air Force does not have depot level maintenance capabilities for the repair of the LRUs/SRUs under study. Once an LRU fails, a corresponding serviceable item is obtained from an inventory location (rotable pool) located at the base where the A4 are deployed, and installed in the failed aircraft; thereby restoring it to full operational capability. These maintenance actions are considered to be at the organizational maintenance level.

The failed item is submitted to the intermediate level maintenance. If depot level maintenance is required, the item, either the LRU or the SRU, is forwarded to a main depot and from there to a repair facility located in the United States, where they are scheduled for repair, and subsequently returned in serviceable condition to the Air Force Base (A.F.B.).

The main steps followed by the LRUs/SRUs from transport from the intermediate repair facility to the depot repair facility now include administrative, transportation and repair delays such as forms preparation, packing and transportation to a main depot, exportation forms preparation and custom inspections in Argentina and in the United States, transportation by ship both ways, warranty acceptance processes, receipt at the main depot, transportation to the A.F.B. and receipt of the LRUs/SRUs.

2. Brazilian A-4 Aircraft Repairable-Item Inventory System

The Brazilian Skyhawks were officially added to the Navy's inventory in October, 1998. They were purchased from Kuwait for operation from the aircraft carrier Minas

Gerais (A-11). Therefore, the operational environment is probably the main difference that exists between the Brazilian and Argentine's A-4s, since the Brazilian Navy A-4s will be more exposed to the sea elements and because of the stress involved in aircraft carrier takeoffs and landings.

Currently, the supporting infrastructure and aircraft maintenance programs are being finalized. Training of Brazilian Skyhawk pilots is being conducted in both Argentina and the United States. Many avionics components are scheduled for upgrading soon, just as the Argentine Air Force has done with their components. Maintenance procedures are also very similar to Argentina's, and the steps to be followed for shipping a faulty item to a main depot and from there to aborad are quite comparable. Thus, for the purpose of this study, they are assumed to be the same in terms of what to do and where to be sent. In this scenario, there is just one naval air station, where the Brazilian A-4 squadron (VF-1) is located.

D. CHAPTER SUMMARY

This chapter provided information regarding to the concept of repairable-item inventory system, mainly focusing on the Argentine and Brazilian A-4 Aircraft Repairable-Item Inventory Systems. Essential terms as operational availability and rotable pool were defined and the different levels of maintenance were discussed.

The next chapter presents the development of our simulation model.

IV. SIMULATION MODEL DEVELOPMENT

> The simulations are powerful "what-if" models, relating unit achievement to the nature of its tasking, methods of operation and levels of logistic and other support. Such models can be used at any stage in the life cycle of the equipment. [Ref. 11]

A. CHAPTER OVERVIEW

Chapter III presented an overview of repairable-item inventory systems emphasizing the procedures used currently in Brazil's and Argentina's A-4 Aircraft Repairable-Item Inventory Systems. The information provided is used in this chapter in order to develop the simulation model. In fact, it represents the scenario on which our model is based.

Chapter IV includes a brief review of the Arena simulation software, data source of all information presented, model description, list of the assumptions made in order to use the model, model validation, and results. These are essential in building a baseline to further assess and draw conclusions for the study.

B. SIMULATION WITH ARENA

At this point, we want to add some comments about the simulation software package used to develop our model.

To attain the purpose of this thesis, we needed a tool that not only would mimic the behavior of our real systems, but would also perform a simulation analysis. Arena software, developed by Systems Modeling Corporation and Optimization Technologies, Inc. was chosen because of its powerful modeling capabilities. Arena also exploits a

heritage of power simulation software in a natural, graphical interface. According to its creators, Arena enables process improvement by simulating core business functions in computer models and allowing users to analyze alternative scenarios [Ref. 12].

> From a practical viewpoint, simulation is the process of designing and creating a computerized model of a real or proposed system for the purpose of conducting numerical experiments to give us a better understanding of the behavior of that system for a given set of conditions. [Ref. 13:p. 7]

Nowadays, since computers and software are extremely powerful and have provided the users with user-friendly interface capability there was no doubt in choosing a computer simulation software to develop our model.

With Arena, we built our model representing the repair process of a selected group of A-4 critical electronic components. By using many available icons and connecting lines, we were able to mimic the actual movement of entities through the system. With this graphic approach, the user can visualize the model as he would visualize the real system.

C. DATA SOURCE

As we previously mentioned, the incorporation of the Douglas A-4 Skyhawk aircraft happened during the year of 1998. However, some collection of data required observations covering periods more than a year. Since Argentina and Brazil were not able to fill our needs completely we targeted other available sources with similar electronic components. In fact, one of these available sources was the U.S. Navy. The observed procedures during an on-site visit to the U.S. Naval Aviation Depot-North

Island, California and the data collected were fundamental in accomplishing this study. The statistical distributions were determined by applying the gathered data to the data input analyzer tool in Arena.

D. MODEL DESCRIPTION

The information supplied from the previous chapter generated the basic scenario in which our model takes place. Now, we are going to describe in more detail the repair process and provide any missing information that applies to our model.

The Argentine Air Force has thirty A-4 aircraft and maintains one Aircraft Intermediate Maintenance Department (AIMD). At present, the Brazilian Naval Air Station has also just one AIMD, since the aircraft carrier Minas Gerais (A-11) is still undergoing upgrading and remodeling. The Brazilian Navy has twenty A-4 aircraft.

We understand that there are differences between the A-4 aircraft models acquired by the two countries. In this study, we focused our attention on similarities and we assumed the completion of equipment upgrading that, in reality, is still in process mainly for the Brazilian Navy.

There are five specific rotable pools, one for each critical LRU. To allow an easier interpretation of the model, the following correlation has been made:

Actual LRU name	Correlated name that appears in the model
Digital Mission Computer (DMC)	LRU_1
Radio Altimeter (RALT)	LRU_2
Air Data Computer (ADC)	LRU_3
Inertial Navigation Unit (INU)	LRU_4
Head up Display Unit (HDU)	LRU_5

We are also considering two specific rotable pools, one for each critical SRU. The main reason why these two SRUs were selected is because of their significant relationship with the failure of the LRU of which each of them pertain. For modeling interpretation purposes only, we are assuming the following correlation:

Actual SRU name	Correlated name that appears in the model
Torque Drive Power Supply Module[1]	SRU_2
Sensor Assembly[2]	SRU_4

Table 4.1 presents the assumed level for each LRU rotable pool, as well as for each of the two SRU's. Note that AAF stands for Argentine Air Force, while BN stands for Brazilian Navy.

Armed Force	LRU_1	LRU_2	LRU_3	LRU_4	LRU_5	SRU_2	SRU_4
AAF	3	2	2	3	3	3	5
BN	2	3	3	2	2	7	5

Table 4.1. LRU/SRU Rotable Pool Levels.

Flight hour rates per aircraft are assumed to be thirty hours per month on average for both A-4 fleets. Based on these observations, LRUs fail according to Table 4.2

[1] The **Torque Drive Power Supply Module** is a subcomponent of the Radio Altimeter, which is identified as LRU_2 during the simulation.

[2] The **Sensor Assembly** is a subcomponent of the Inertial Navigation Unit, which is identified as LRU_4 during the simulation.

following exponential distributions with MTBF (mean time between failures) as specified.

LRU	AAF		BN	
	MTBF (days)	Distribution	MTBF (days)	Distribution
LRU_1	220.5	Exponential	147.0	Exponential
LRU_2	270.0	Exponential	180.0	Exponential
LRU_3	174.0	Exponential	116.0	Exponential
LRU_4	146.0	Exponential	97.4	Exponential
LRU_5	272.0	Exponential	181.0	Exponential

Table 4.2. LRUs' Mean Time Between Failures.

When a LRU fails, a RFI (ready-for-issue) LRU from the RP is installed. The faulty LRU becomes an input to the AIMD to be repaired and returned to the RP as a RFI item. The time for removal/installation of LRU has triangular distribution with (0.250,0.375,0.500)[3] days. Time for inspection to determine the appropriate level of maintenance (i.e. I-level or D-level maintenance) follows a uniform distribution UNIF(0.125,0.375)[4], measured in days. Table 4.3 provides the percentage of the LRUs at AIMD that are considered BCM (beyond capability of maintenance) and are sent abroad (D-level maintenance).

[3] TRIA(val_1,val_2,val_3) = Triangular distribution, where val_1 is the minimum value, val_2 is the mode value, and val_3 is the maximum value.

[4] UNIF(val_1,val_2) = Uniform distribution, where val_1 is the minimum value and val_2 is the maximum value.

LRU	Percentage of LRUs considered BCM
LRU_1	70%
LRU_2	88%
LRU_3	80%
LRU_4	66%
LRU_5	69%

Table 4.3. Percentages of LRUs at AIMD Considered BCM.

When one LRU fails, and there is no RFI LRU available from the rotable pool, the aircraft will be grounded until a RFI LRU is available. Ninety-nine percent of all LRU_2 failures are due to a failure on SRU_2. Similarly, fifty-three percent of all LRU_4 failures are due to a failure on SRU_4. All faulty SRU is considered beyond capability of maintenance, and is shipped abroad for repairing. The situation for replacing a faulty SRU is very similar to the replacement of a faulty LRU, i.e. whenever the LRU failure is related to a SRU problem, a RFI SRU from the RP is installed, and then the LRU is in ready-for-issue condition again. The time for removal/installation of SRU has triangular distribution with (0.25,1.00,1.50) days. Time for inspection to analyze the SRU failure, and to determine which SRU is responsible for the LRU failure follows a uniform distribution UNIF(0.25,1.00), measured in days.

When the LRU failure is not related to failure of one of the specific SRU previous mentioned, the time to repair/replace the faulty part at AIMD follows the distribution presented in Table 4.4. MTTR (mean time to repair/replace) is as specified.

LRU	MTTR (days)
LRU_1	EXPO (1.040)[5]
LRU_2	LOGN(0.410,0.260)[6]
LRU_3	EXPO(1.120)
LRU_4	EXPO(0.364)
LRU_5	EXPO(1.725)

Table 4.4. Mean Time to Repair/Replace Faulty LRUs at AIMD.

Table 4.5 presents the time spent when a faulty part is sent abroad for repairing.

Activity	Time Consumed
Northbound route – administrative process (including warranty verification process time) plus transportation.	UNIF (30,45)
Southbound route– administrative process plus transportation.	UNIF (20,40)
Repairing LRU at D-level	UNIF (30,90)
Repairing SRU at D-level	UNIF (30,90)

Table 4.5. Total time, expressed in days, consumed for repair a faulty part abroad (transportation mode: sea mode).

Figure 4.1 shows the flowchart of the model previously described, concerning the repair process for LRU_1, 3 and 5. Figure 4.2 presents the flowchart of the model previously described, but it concerns the repair process for LRU_2 and 4. Note that in Figure 4.2 we included testing of the SRU_2 and 4. As previous observations showed, there is significant relationship between them and the failure that occurred on each LRU they belong to which means that most of the time when a respective LRU fails, the failure is due to one of these two SRUs, whichever applies.

[5] EXPO(val_1) = Exponential distribution, where val_1 is the mean.

[6] LOGN(val_1,val_2) = Lognormal distribution, where val_1 is the mean and val_2 is the standard deviation.

Appendix A includes a static view of the simulation model animation. Notice that we organized the model in such a manner that explicitly shows the path each LRU/SRU follows during the replace/repair process. There is also a section denominated "Control Panel", where we placed the resources related to data updating and output settings, as well as the representation of the rotable pools. In this case, the model can be easily changed to respond to different "what-if" scenarios.

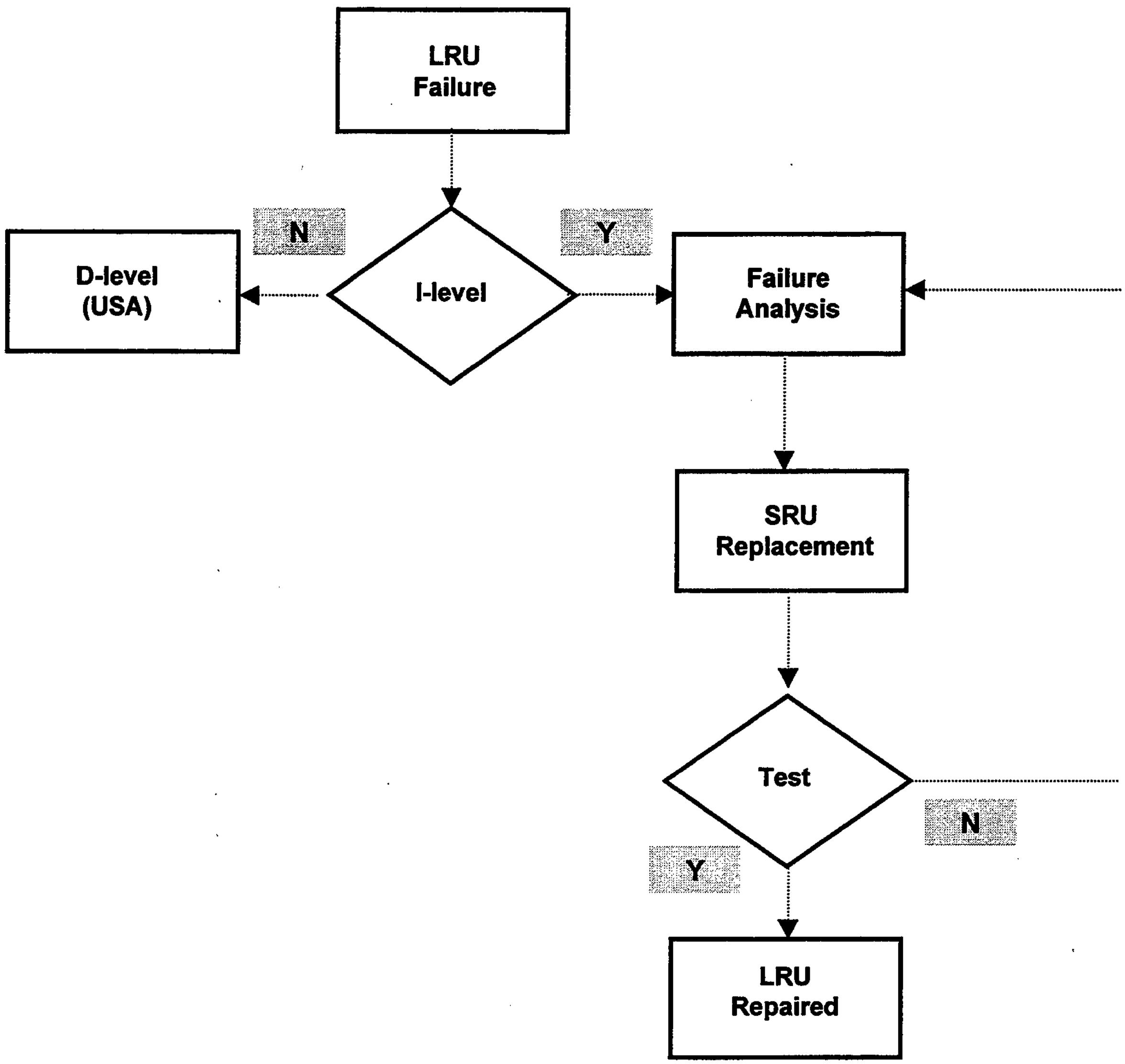

Figure 4.1 LRU_1, 3 and 5 Repair Cycle.

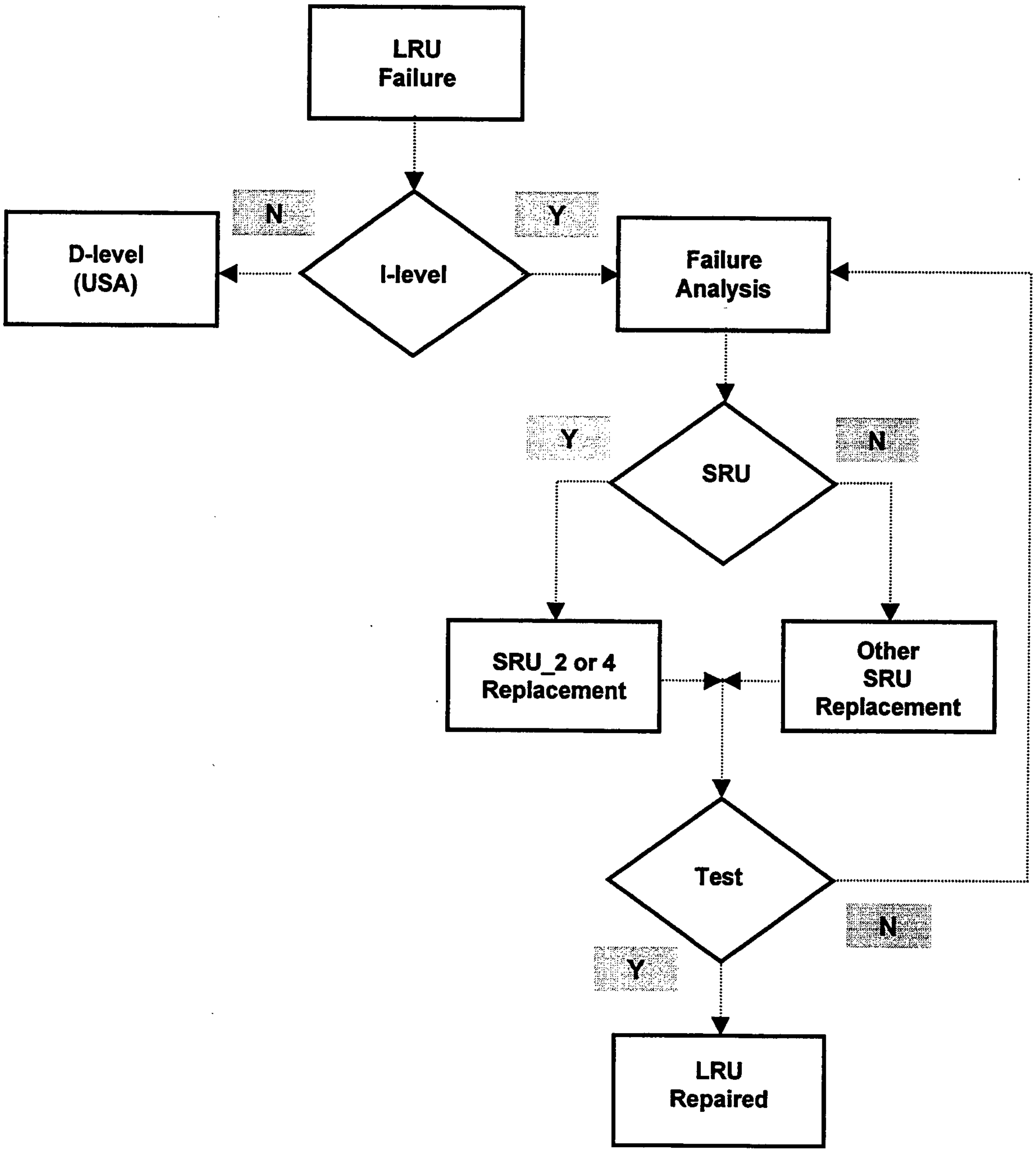

Figure 4.2. LRU_2 and 4 Repair Cycle.

E. ASSUMPTIONS

The developed model intends to furnish the logistics decision makers with a decision support tool for the analysis of the operational availability of A-4 aircraft fleets, as well as to evaluate the cost-effectiveness of the repairable-item inventory systems. On the other hand, we had to limit the level of details and variations we face when rendering an accurate simulation model, otherwise this thesis would be very long. Therefore, the following assumptions were made to use the model.

- We are analyzing electronic components. Hence, we assume no need for preventive maintenance.
- The LRUs/SRUs in this model never completely fail such that they cannot be made serviceable. No condemnations are possible.
- Spares units do not fail while in the rotable pool.
- Each aircraft carries a single unit of each LRU/SRU.
- Failures are always due to one, and only one of the LRUs. Consequently, LRUs do not fail at the same time.
- The AIMD operates eight hours a day.
- There is a single point of destination in the United States and a single point of origin for LRUs/SRUs transportation computations (time and cost estimations).
- No cannibalizations are considered. Hence, the operational availability of the fleets may be less in the simulation model than in real circumstances, but we considered the fact that cannibalization doubles the maintenance man-hours required to repair the aircraft and can induce malfunctions to an otherwise serviceable LRU through additional handling. This is why cannibalization is not modeled in our study.

F. VALIDATION

We set up our simulation model replication length for a period equivalent to ten years because this is assumed to be the LRUs' useful life period which is representative of a military avionics system nowadays.

We ran fifty replications for the Argentine scenario and fifty more for the Brazilian's. This ensured a number of observations large enough for each run to provide an average operational availability value that is statistically sound.

Counters were placed along the model (see Appendix A). They provided accountability for the number of parts flowing through the model during any time, as well as for the number of aircraft in queue due to the limitation of LRUs/SRUs in serviceable conditions. These counters are very helpful in determining the potential bottlenecks of the system.

G. RESULTS

From running the simulation model, the results showed the Brazilian Navy A-4 aircraft fleet operating with an A_0 of 0.83975, or 83.98 percent, while the Argentine's achieved 0.86578, or 86.58 percent.

Table 4.6 summarizes both countries' settings and results. We included in this table the total number of parts being sent abroad for repair in ten years and is represented in two ways: average number and estimated number with 95 percentile point (i.e., probability that the number will exceed this value will be 0.05). The numbers were collected from the Arena's output analyzer, and they provide fundamental information for

the decision makers when estimating transportation costs, as well as to support repair part contracting decisions.

	Brazilian Navy		Argentine Air Force	
	20 A/C LRUs RP levels = 2,3,3,2,2 SRUs RP levels = 7,5 LRUs MTBF = 147,180,116,97.4,181		30 A/C LRUs RP levels = 3,2,2,3,3 SRUs RP levels = 3,5 LRUs MTBF = 220.5,270,174,146,272	
LRU/SRU	**AVERAGE**	**95 PERCENTILE POINT**	**AVERAGE**	**95 PERCENTILE POINT**
LRU_1	58	64	53	59
LRU_2	53	60	51	57
LRU_3	85	94	89	97
LRU_4	87	95	115	124
LRU_5	43	49	39	44
SRU_2	8	9	8	9
SRU_4	25	27	31	35
TOTAL LRUs	326	362	347	381
TOTAL SRUs	33	36	39	44
A_0	**0.83975**		**0.86578**	

Table 4.6. Summary of the settings and simulation results for the Brazilian Navy and the Argentine Air Force A-4 fleets.

H. CHAPTER SUMMARY

This chapter covered the entire process of developing our simulation model. We started with a brief review of the Arena software which was the tool we chose to mimic the behavior of our real systems. Then, we provided a detailed description of the model and a corresponding list of assumptions made to use the model. We also showed how we validated the model and the resulting A_0 for each country.

Our next step is to develop and simulate a scenario where the Brazilian Navy and the Argentine Air Force collaborate on the inventory management of their A-4 fleets. Therefore, Chapter V will present the development of our Coalition Model.

V. COALITION MODEL

A. CHAPTER OVERVIEW

Based on the very positive and receptive environment to embrace the idea of inventory consolidation between the Brazilian Navy and the Argentine Air Force, as we showed in Chapter II, and using the model we presented in Chapter IV, which is suitable for both Armed Forces, we propose the development of a coalition model. Hence, this chapter defines the basic parameters to be used for this joint scenario and projects the resulting benefits in terms of operational availability improvement.

B. COALITION MODEL DESCRIPTION

The coalition model is based on the same structure and data used for the Argentine and Brazilian models except for the number of aircraft that change to fifty A-4 aircraft and the MTBF of each of the LRUs that are calculated as a weighted average (W.A.) of the Brazilian and Argentine LRUs MTBF.

The coalition model LRU/SRU inventory levels are shown in Table 5.1. These numbers are the result of adding the existent inventories of each RP of both countries.

Coalition	LRU_1	LRU_2	LRU_3	LRU_4	LRU_5	SRU_2	SRU_4
AAF + BN	5	5	5	5	5	10	10

Table 5.1. LRU/SRU Rotable Pool Levels (Coalition Model).

The MTBFs, presented in Table 5.2, were obtained from the following computation (expressed in days, using data from Chapter IV, Table 4.2):

$$W.A.\ LRU\_1 = (20*147 + 30*220.5)/50 = 191$$

$$W.A.\ LRU\_2 = (20*180 + 30*270)/50 = 234$$

$$W.A.\ LRU\_3 = (20*116 + 30*174)/50 = 151$$

$$W.A.\ LRU\_4 = (20*97.4 + 30*146)/50 = 127$$

$$W.A.\ LRU\_5 = (20*181 + 30*272)/50 = 236$$

LRU	**AAF + BN**	
	MTBF (days)	**Distribution**
LRU_1	191	Exponential
LRU_2	234	Exponential
LRU_3	151	Exponential
LRU_4	127	Exponential
LRU_5	236	Exponential

Table 5.2. LRUs' Mean Time Between Failures (Coalition Model).

C. RESULTS

After running 50 replications, the results show an increase in the operational availability from 0.83975 and 0.86578, for the Brazilian and Argentine fleets, respectively (see Chapter IV, Table 4.6), to a value of 0.88838, or 88.84 percent, for both fleets operating under the coalition model.

Table 5.3 summarizes the operational scenarios for both Armed Forces before and after the proposed coalition.

	Brazilian Navy		Argentine Air Force		Coalition Model	
	20 A/C LRUs RP levels = 2,3,3,2,2 SRUs RP levels = 7,5 LRUs MTBF = 147,180,116,97.4,181		30 A/C LRUs RP levels = 3,2,2,3,3 SRUs RP levels = 3,5 LRUs MTBF = 220.5,270,174,146,272		50 A/C LRUs RP levels = 5,5,5,5,5 SRUs RP levels = 10,10 LRUs MTBF = 191,234,151,127,236	
LRU/SRU	**AVERAGE**	**95 PERCENTILE POINT**	**AVERAGE**	**95 PERCENTILE POINT**	**AVERAGE**	**95 PERCENTILE POINT**
LRU_1	58	64	53	59	107	115
LRU_2	53	60	51	57	103	112
LRU_3	85	94	89	97	178	188
LRU_4	87	95	115	124	205	215
LRU_5	43	49	39	44	81	89
SRU_2	8	9	8	9	14	16
SRU_4	25	27	31	35	55	59
TOTAL LRUs	326	362	347	381	674	719
TOTAL SRUs	33	36	39	44	69	75
A_0	**0.83975**		**0.86578**		**0.88838**	

Table 5.3. Summary of the settings and simulation results (before and after the Coalition Model).

The simulation results also show average reductions of about three percent and seven percent in the total number of LRUs and SRUs, respectively, sent to depot level maintenance. These expected reductions are due to the effects of inventory consolidation. Figures 5.1 to 5.3 illustrate these reductions.

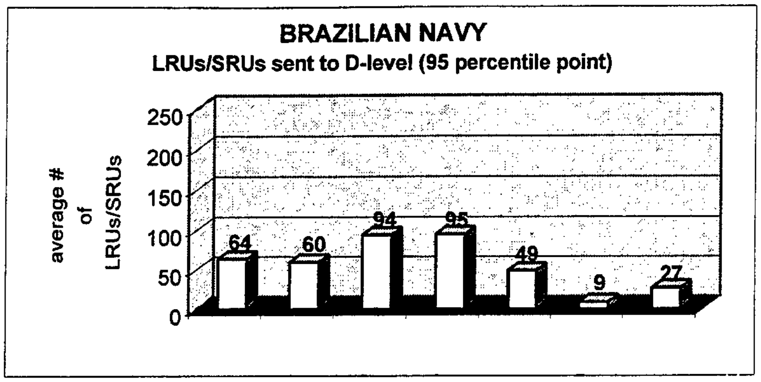

Figure 5.1 Brazilian Navy – LRUs/SRUs sent to D-level (95 percentile point).

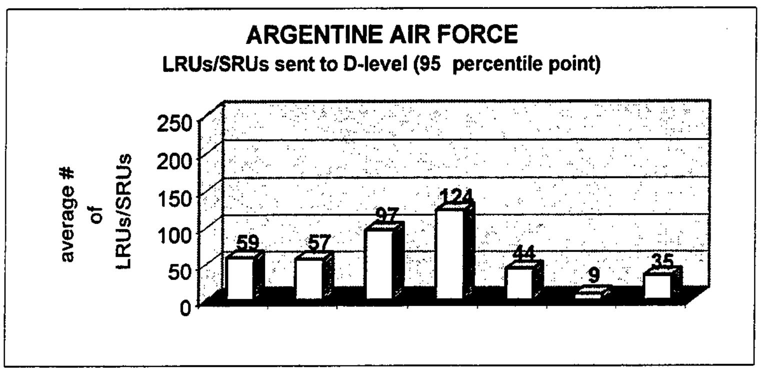

Figure 5.2. Argentine Air Force – LRUs/SRUs sent to D-level (95 percentile point).

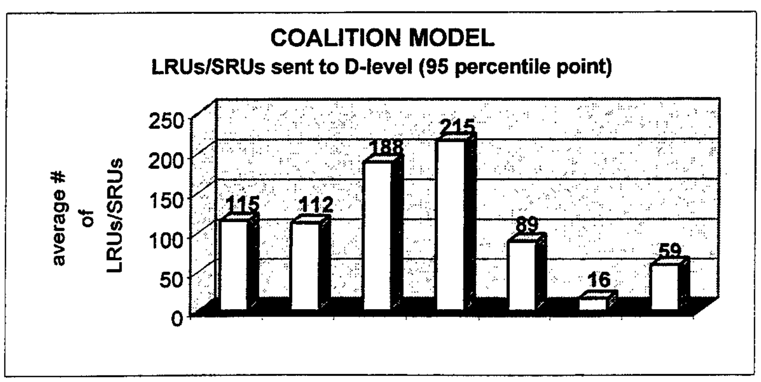

Figure 5.3. Coalition Model – LRUs/SRUs sent to D-level (95 percentile point).

D. CHAPTER SUMMARY

The simulation results showed the advantages in terms of operational availability for the coalition model. The improvement in A_0 for both aircraft fleets might be materialized through a joint total asset visibility administration for the LRUs/SRUs sent

to depot-level maintenance. The implementation of a common administration can be the subject of further studies.

All the research developed in the next chapters will be based on the coalition model previously described. Therefore, Chapter VI presents a simulation based on the same coalition model, but with reduced transportation time in order to determine the effects of turnaround time reduction on the operational availability of the aircraft fleets.

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VI. COALITION MODEL WITH REDUCED TRANSPORTATION TIME

A. CHAPTER OVERVIEW

In the previous chapter, a coalition model was developed showing the advantages in terms of operational availability for both countries.

In this chapter, we run the coalition model again, but this time we reduced the transportation time to analyze the impact on the operational availability of the A-4 fleets.

B. TRANSPORTATION TIME REDUCTION

The current time spent when a faulty part has to be sent abroad to be repaired follows a uniform distribution UNIF(30,45), expressed in days, as previously shown in Chapter IV, Table 4.5 (Northbound route). Similarly, it takes an average time of UNIF(20,40) for the part to return from the repair facility abroad (Southbound route). These times include administrative process delays and transportation.

Since the transportation by sea mode adopted by both Armed Forces is the main contributor to such long periods, we propose a reduction of transportation time by changing the transportation mode to air mode. Our research showed that using the air mode significantly reduced transportation time. These results are shown in Table 6.1.

Activity	Time Consumed
Northbound route – administrative process (including warranty verification process time) plus transportation.	UNIF (10,15)
Southbound route– administrative process plus transportation.	UNIF (8,13)
Repairing LRU at D-level	UNIF (30,90)
Repairing SRU at D-level	UNIF (30,90)

Table 6.1. Total time, expressed in days, consumed for repair a faulty part abroad (transportation mode: air mode).

C. DATA COLLECTION

We collected data regarding the cost and time consumption for air mode transportation through a survey where domestic and international freight forwarders provided their estimates. Table 6.2 shows the average cost of transportation by air mode for each LRU/SRU, including express and expedited modes.

LRU/SRU	Express Mode (2 days) Shipping + Insurance (US$)	Expedited Mode (4 days) Shipping + Insurance (US$)
LRU_1	1,401.00	1,120.00
LRU_2	432.00	346.00
LRU_3	1,396.00	1,117.00
LRU_4	1,587.00	1,270.00
LRU_5	1,589.00	1,270.00
SRU_2	277.00	222.00
SRU_4	277.00	222.00

Table 6.2. Average Air Mode Transportation Costs.

The transportation time used in the model with reduced transportation time corresponds to the expedited mode that demands four days for door-to-door service.

D. RESULTS

After running a simulation of fifty replications, a large enough sample to diminish the random effects, we obtained an increase of approximately seven percent in the operational availability (from 0.88838 to 0.95034) without the need to increase the inventory level. Appendix B presents the corresponding simulation output.

The impact on the operational availability through the reduction of transportation time can be explained by the decrease in the number of grounded aircraft waiting for spare parts at the rotable pools. This phenomenon illustrates the fundamental relationship between work in process, cycle time, and throughput called the Little's Law.

According to Hoop and Spearman [Ref. 13], Little's Law, named for John D.C. Little who provided the mathematical proof, is represented by

$$\mathbf{WIP = TH * CT}$$

where:

- Work In Process (**WIP**): It is the inventory between the start and end points of the repair process.
- Cycle Time (**CT**): It is also called throughput time. It is the average time from release of a repair job at the beginning of the repair routing until it reaches an inventory point at the end of the routing (that is, the time the part spends as WIP).
- Throughput (**TH**): It is the average output of the repair process per unit of time, also referred as throughput rate.

By reducing transportation time WIP is reduced, as we can see by comparing Figures 6.1 and 6.2. Note the significant reduction in the average number of grounded aircraft waiting for spare parts from the rotable pools.

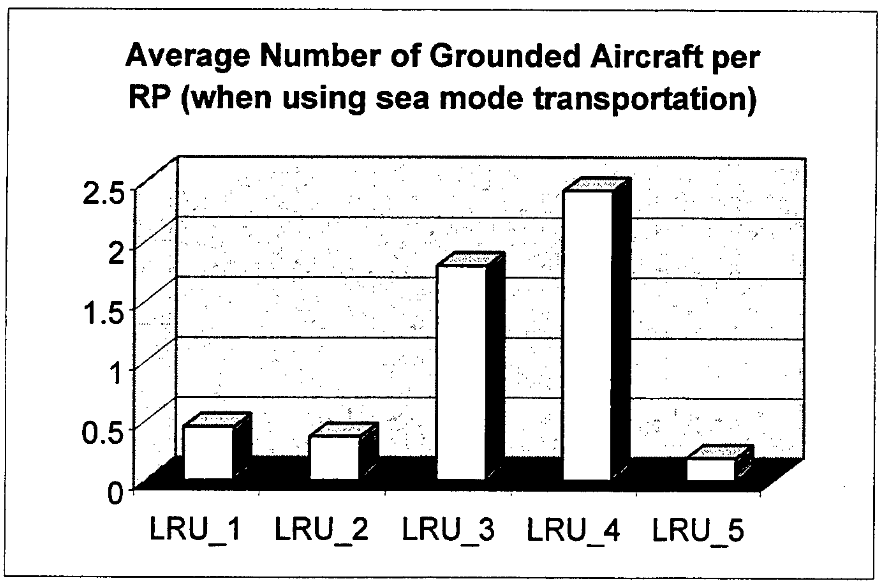


Figure 6.1. Average Number of Grounded Aircraft per RP (when using sea mode transportation)

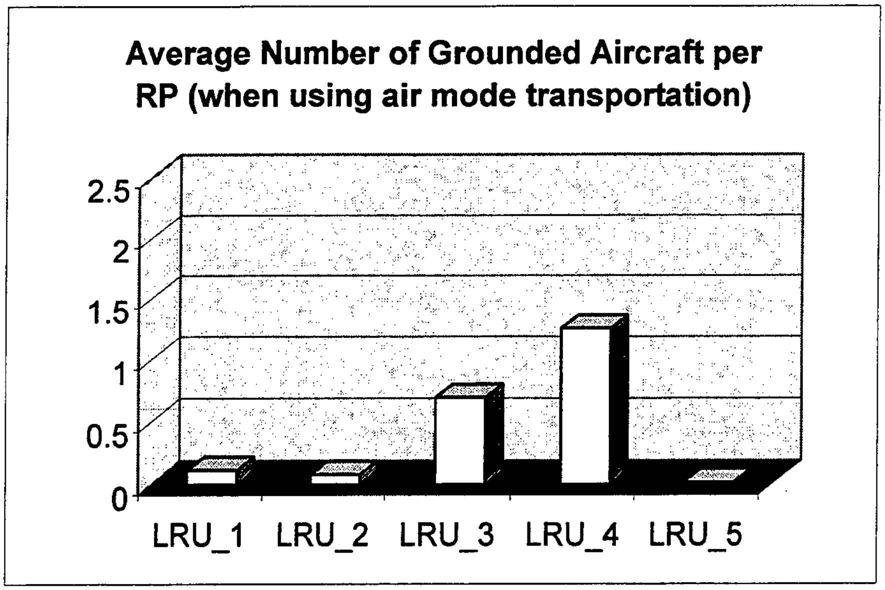


Figure 6.2. Average Number of Grounded Aircraft per RP (when using air mode transportation).

E. CHAPTER SUMMARY

This chapter analyzed the impact of transportation time reduction on the operational availability. The simulation results showed an increase of seven percent in A_0 without the need to increase the inventory level just by reducing transportation time.

In the Chapter VII, we will develop a metamodel that can be used to determine the optimum LRU/SRU inventory levels given a specific operational availability.

VII. METAMODEL DEVELOPMENT

> Analysts use the simulation model as a surrogate because it is impractical to construct multiple prototype versions of the real system, or because cost or other constraints prohibit experimentation with the real system. These models themselves may be quite complex, and so simpler approximations are often constructed; models of the model, or metamodels. (Kleijen, 1987) [Ref. 15]

A. CHAPTER OVERVIEW

In the previous chapter, we ran a simulation of the coalition model with reduced transportation time. This showed the benefits for both countries in terms of operational availability.

In this chapter, we develop a metamodel that will be useful in the determination of the optimal inventory levels given a desired operational availability.

B. MULTIPLE REGRESSION ANALYSIS - LITERATURE REVIEW

> Regression models are often applied by management scientists to analyze simulation data as well as real-world data. It is well recognized that the data of a simulation experiment can indeed be analyzed through a regression model that serves as a metamodel (see Kleijnen 1987, p. 241). [Ref. 16:p.1164]

Multiple linear regression provides a manageable way to control statistically for the effects of several independent variables. Its use requires assuming that the effects of the various independent variables on the dependent variable are additive. That is, the marginal effect on the dependent variable of a unit change in any of the independent variables remains the same no matter what the values of the independent variables are.

The expression of a linear regression model in mathematical form is:

$$Y = a_0 + a_1 * x_1 + a_2 * x_2 + \ldots\ldots + a_k * x_k + e$$

where Y is the dependent variable and x_1, x_2, ...x_k are the k independent variables. The intercept parameter, a_0, also called the constant, is the expected value of Y if all the independent variables equals zero. The other parameters, a_1, a_2, ... a_k, which are called slope parameters, measure the marginal impacts of the independent variables on the dependent variable. If, for instance, we were to increase x_1 by one unit while holding the values of the other independent variables constant, Y would change by an amount a_1. Similarly, each of the other coefficients measures the marginal effect of a unit change in its variable on the dependent variable. The last term of the equation, e, is an error term that incorporates the cumulative effect on Y of all the factors not explicitly included in the model. [Refs. 17 and 18]

C. METAMODEL EQUATION

The formulation of the metamodel equation started with the running of simulations for the coalition model using air mode transportation. We ran 128 simulations that represent inventory level combinations within the range of the existent inventories. Each one of the simulation runs is a result of 50 replications. This provides a large enough sample size, or number of observations to ensure statistically sound data results. The results of all 128 simulations are shown in Appendix C. Then, by using Microsoft Excel, we conducted a multiple regression analysis.

From the regression analysis, the metamodel equation was defined as

$$\mathbf{A_0 = 0.755 + 0.0064*X_{LRU\_1} + 0.0057*X_{LRU\_2} + 0.0103*X_{LRU\_3} + 0.0112*X_{LRU\_4} + 0.0040*X_{LRU\_5} + 0.00004*X_{SRU\_2} + 0.0007*X_{SRU\_4}}$$

where Xi represents the number of LRUs/SRUs in their respective rotable pools.

The multiple regression analysis provides the coefficients for the LRUs/SRUs in the metamodel equation, as well as the y-intercept of 0.755, which means that an A_0 of 75.5 percent can be achieved with inventory levels equal zero.

The coefficient values represent the marginal contribution to the operational availability of each one of the LRUs/SRUs. For example, for every additional LRU_1 added to the initial inventory level, fleet operational availability increases by 0.64 percent (coefficient value is 0.0064). The summary output obtained from Excel is displayed in Appendix D. Notice from the metamodel equation that SRU_2 coefficient does not significantly contribute to increasing the A_0.

We validated the metamodel equation using the same numbers of LRUs/SRUs for the simulation model in Arena and for the equation. Afterwards, we contrasted the resulting A_0. No significant differences were found.

D. RESULTS

From the analysis of the metamodel we can see that the two LRUs that have the highest marginal contributions to the A_0 are the LRU_4 and LRU_3. Each one of them has a marginal contribution to the operational availability of 1.12 percent and 1.03 percent, respectively.

The value of the constant in the metamodel equation shows that it is possible to achieve 75.5 percent of operational availability with zero inventory. This is possible at the expense of the reduction in the transportation cycle time. In addition, we concluded that SRU_2 has a very low marginal contribution to the operational availability. Thus, it can be disregarded from the equation.

E. CHAPTER SUMMARY

In this chapter, we developed a metamodel equation using multiple regression analysis. The metamodel showed the marginal contribution of different components to the operational availability.

In the next chapter, we will develop a linear programming model to find the optimal inventory combination that minimizes costs given a value of operational availability.

VIII. SENSITIVITY ANALYSIS

A. CHAPTER OVERVIEW

In the previous chapter, we developed a metamodel equation that will be useful in the process of determining the optimal inventory combination.

Chapter VIII analyzes the impact of spare level variation on operational availability. We are looking for the inventory combination that reaches an operational availability of 0.88838, a value comparable to the scenario for the coalition model, using sea mode transportation. For this purpose, we graph the marginal contribution of each LRU/SRU to A_0 and develop a linear programming model.

B. SPARE LEVEL VS. OPERATIONAL AVAILABILITY

Figures 8.1 to 8.7 show how the operational availability changes due to variations in one particular rotable pool, *ceteris paribus*[1]. This means that, while one specific rotable pool level changes, there are no changes in the remaining rotable pools.

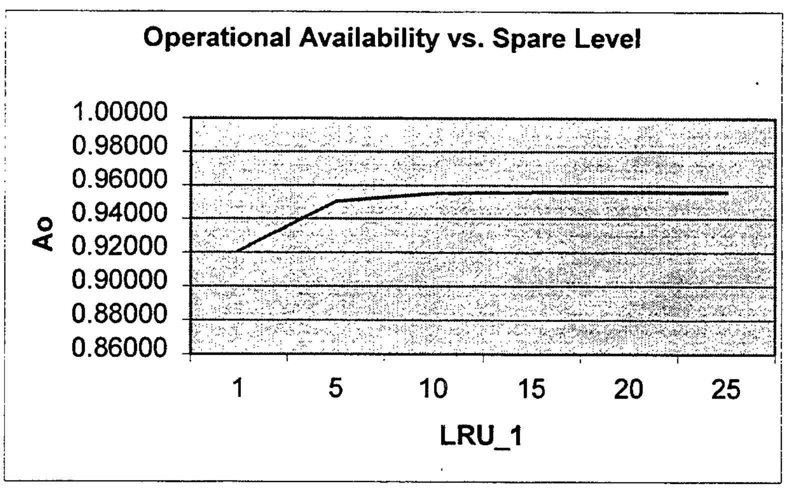


Figure 8.1. Operational Availability vs. Spare Level – LRU_1.

[1] *Ceteris paribus* is a Latin phrase meaning "all other factors held constant"

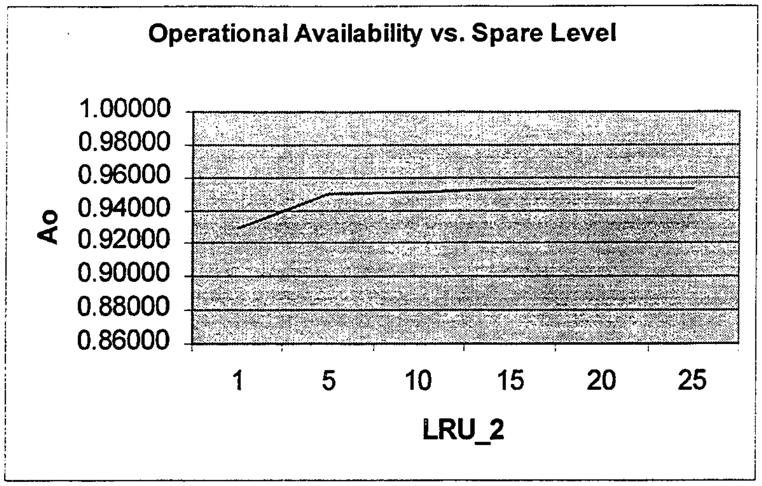


Figure 8.2. Operational Availability vs. Spare Level – LRU_2.

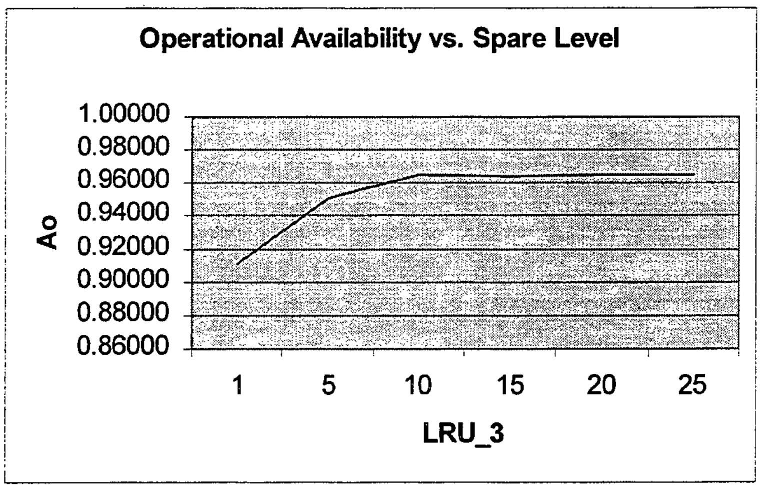


Figure 8.3. Operational Availability vs. Spare Level – LRU_3.

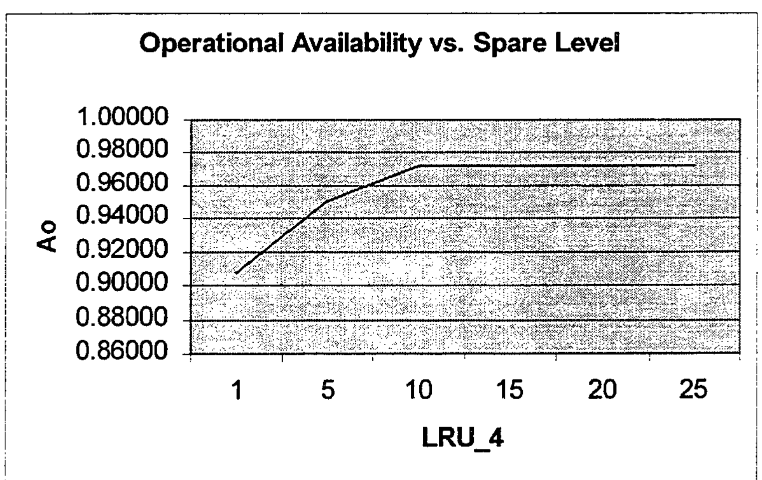


Figure 8.4. Operational Availability vs. Spare Level – LRU_4.

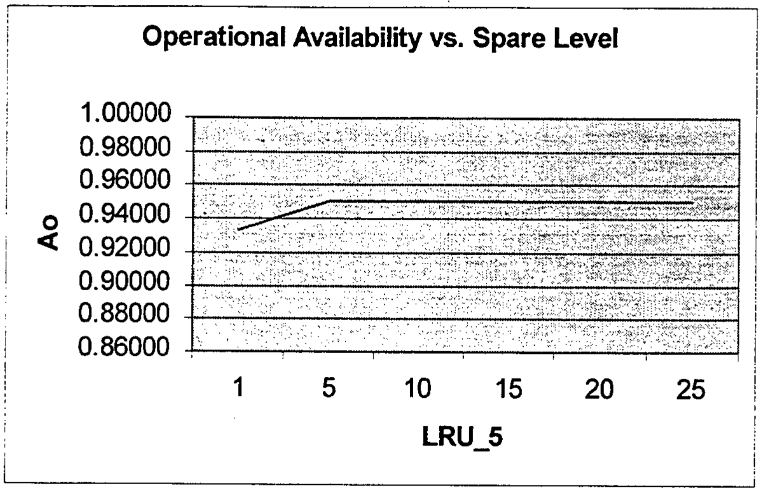


Figure 8.5. Operational Availability vs. Spare Level – LRU_5.

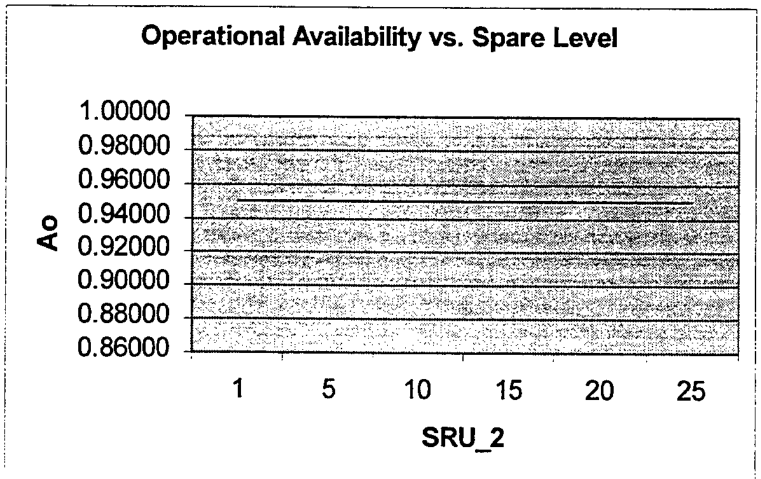


Figure 8.6. Operational Availability vs. Spare Level – SRU_2.

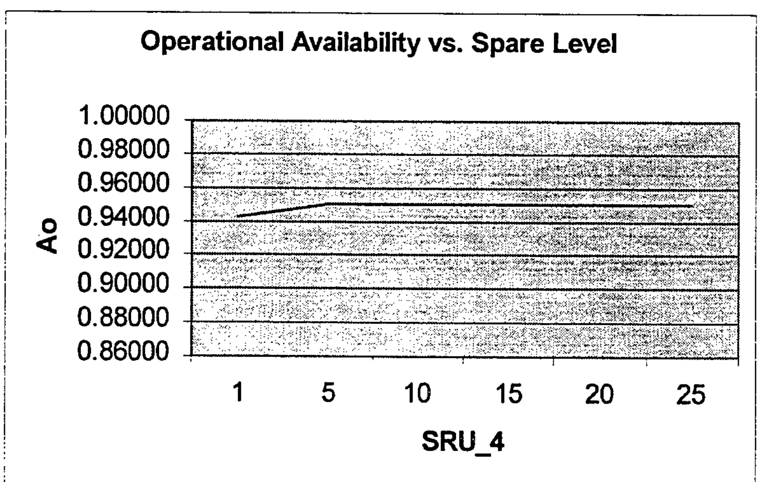


Figure 8.7. Operational Availability vs. Spare Level – SRU_4.

These graphs were built using the marginal contribution of the different electronic components to the operational availability, as was shown in the metamodel, and by running new simulations with inventory levels out of the range of the metamodel.

As these graphs showed, A_0 increases from adding spare parts, but this follows a diminishing rate until the point where A_0 stabilizes. From this point, there is no contribution and A_0 remains the same. This is not true only for the SRU_2, which does not contribute to A_0 since its coefficient in the metamodel equation is very low (see Chapter VII).

C. COST MINIMIZATION USING LINEAR PROGRAMMING

1. Linear Programming – Literature Review

Linear programming is a widely used mathematical technique designed to help managers in planning and decision making for relative resource allocation.

Linear programming problems seek to maximize or minimize some quantity (objective function), usually profit or cost, subject to limited resources (the constraints).

The objective and constraints in linear programming problems are expressed in terms of linear equations or inequalities. [Ref. 19]

2. Cost Minimization

Table 8.1 shows the acquisition costs of the different electronic components.

LRU/SRU	Acquisition Cost (US$)
LRU_1	91,754.00
LRU_2	30,800.00
LRU_3	46,763.00
LRU_4	78,225.00
LRU_5	180,000.00
SRU_2	5,000.00
SRU_4	5,000.00

Table 8.1. LRU/SRU Acquisition Cost.

These values are included in the objective function of the linear programming model, which is stated as follows:

- **Objective Function:**

Minimize Costs

$$\mathbf{91754*X_{LRU\_1}+30800*X_{LRU\_2}+46763*X_{LRU\_3}+78225*X_{LRU\_4}+180000*X_{LRU\_5}}$$
$$\mathbf{+5000*X_{SRU\_2}+5000*X_{SRU\_4}}$$

where X_{LRU_i} and X_{SRU_i} represent the number of LRUs/SRUs that satisfies the minimization of the objective function given the following constraints:

- **Constraints**

The first constraint was provided by the metamodel equation obtained in Chapter VII, and is written as follows:

$$\mathbf{0.88838 = 0.755+0.0064*X_{LRU\_1}+0.0057*X_{LRU\_2}+0.0103*X_{LRU\_3}+0.0112*X_{LRU\_4}}$$
$$\mathbf{+0.0040*X_{LRU\_5}+0.00004*X_{SRU\_2}+0.0007*X_{SRU\_4}}$$

where 0.88838 is the desired operational availability, and the other coefficients in the equation represent the marginal contribution to the operational availability of each one of the electronic components.

We assume that the feasible solutions must consider an inventory level of at least one component for each RP. This is expressed as follows:

$$\mathbf{X_{LRU\_1} \geq 1;\ X_{LRU\_2} \geq 1;\ X_{LRU\_3} \geq 1;\ X_{LRU\_4} \geq 1;\ X_{LRU\_5} \geq 1;\ X_{SRU\_2} \geq 1;\ X_{SRU\_4} \geq 1}$$

The following constraints assume that the solutions are limited to the range of the existent inventory. This range is the one where the metamodel is valid.

$$\mathbf{X_{LRU\_1} \leq 5;\ X_{LRU\_2} \leq 5;\ X_{LRU\_3} \leq 5;\ X_{LRU\_4} \leq 5;\ X_{LRU\_5} \leq 5;\ X_{SRU\_2} \leq 10;\ X_{SRU\_4} \leq 10}$$

3. Results

Using Microsoft Excel and QM for Windows software, we finally obtained the optimal spare part levels as shown in Table 8.2.

LRU/SRU	Optimal Inventory Level
LRU_1	1
LRU_2	5
LRU_3	5
LRU_4	3
LRU_5	1
SRU_2	1
SRU_4	10

Table 8.2. LRU/SRU Optimal Inventory Level.

Appendix E provides the Microsoft Excel answer report for this linear programming problem.

D. CHAPTER SUMMARY

In this chapter, we showed the use of a linear programming model where one of the constraints was given by the metamodel equation developed in Chapter VII. The use of the linear programming allowed us to find the combination of spare parts that minimize the inventory costs given an operational availability.

In the next chapter, we will analyze the cost-effectiveness of choosing between the alternatives "current transportation time (sea mode transportation) with existing inventory" and "reduced transportation time (air mode transportation) with optimal number of spare parts," which was obtained in this chapter.

IX. COST-EFFECTIVENESS ANALYSIS

A. CHAPTER OVERVIEW

In the previous chapters, we ran simulations considering two scenarios, one with current transportation time (sea mode), and the other with reduced transportation time (air mode). We presented the advantages in terms of operational availability resulting from the transportation time reduction. Then, in Chapter VIII, we reduced the inventory level to an optimum that minimized costs while reaching the same operational availability as in the scenario with no reduction in transportation time.

In this chapter, we perform a cost-effectiveness analysis in order to show potential savings from reducing both transportation time and inventory level, while operational availability remains unaltered. We use Net Present Value (NPV) and Monte Carlo simulation sensitivity analysis to estimate the risk of the decision making.

B. LITERATURE REVIEW

1. Net Present Value

Analysts evaluate projects using the net present value criterion. By definition, the net present value (NPV) of a project equals the present value of the benefits, PV(B), minus the present value of the costs, PV(C), i.e.:

$$\mathbf{NPV = PV(B) - PV(C)}$$

Equivalently, the NPV of a project equals the present value of the net benefits. To understand the equivalence, consider a project with an expected life of n years. Let,

$$B_t = \text{total benefits arising in year } t \ (t = 0,1,2\ldots n)$$

$$C_t = \text{total costs arising in year } t \ (t = 0,1,2\ldots n)$$

Thus, the annual net benefits equal the difference between annual total benefits and annual total costs, that is, $B_t - C_t$ ($t = 0,1,2...n$). The present value of the net benefits of a project is given by:

$$\text{NPV}= \sum_{t=0}^{\infty} Bt - Ct / (1+i)^t$$

where i is the discount rate and t the number of periods for discounting. [Ref. 18]

2. Real Discount Rate

In order to calculate the NPV of a project, analysts apply a real discount rate to future costs and benefits that are expressed in real dollars. If analysts decide that the market interest rate facing the decision maker is the appropriate discount rate, then, because it is nominal, they must adjust for the expected inflation rate to arrive at the appropriate real discount rate. The real discount rate can be written as:

$$\mathbf{r = (i - m) / (1+m)}$$

where i is the nominal discount rate and m is the expected rate of inflation. [Ref. 18]

3. Monte Carlo Analysis

Monte Carlo analysis provides a way to estimate the distribution of net benefits by explicitly treating assumed parameter values as random variables. It is especially useful when the risk of the policy is of particular concern and the parameters have non-uniform distributions or the formula for the calculation of net benefits involves the parameters in other than simple sums. If we cannot distinguish between two projects in terms of expected values of net benefits, we may be more confident in recommending the one with the smaller variance because it has a higher probability of producing realized net benefits near the expected value. [Ref. 18]

4. Crystal Ball Software

Crystal Ball is a user-friendly, graphically forecasting and risk analysis program that takes the uncertainty out of decision making. Using Monte Carlo Simulation, Crystal Ball displays results in a forecast chart that shows the entire range of possible outcomes and the likelihood not achieving each of them. [Ref. 20]

C. ANALYSIS

We developed an analysis to compare two scenarios. The first one with current transportation time and inventory levels, where we made the following assumptions:

- The net present values are calculated considering acquisition costs and average transportation costs per year, over a period of ten years. Thus, total cost is equal acquisition cost plus transportation cost.
- The sea mode freight rates rise gradually an average of 1 percent per year. [Ref. 21]
- The discount rate is 10 percent and the inflation rate is equal to 4 percent.
- There are hikes in the sea mode freight rates of 10 percent over the expected average rates every five years. [Ref. 21]
- Average transportation costs per year follows a normal distribution using the data displayed in Chapter VI, Table 6.2.
- The calculation of the NPV considers two alternatives. First, a standard deviation of 20 percent of the average transportation costs. Second, a standard deviation of 30 percent.

The second scenario is based on reduced transportation time and reduced inventory levels that minimize costs while reaching the same operational availability as the first scenario. The assumptions made for the first scenario are valid here except for the following:

- The air mode freight rates rise gradually an average of 3 percent per year. [Ref. 21]

- There are hikes in the average air mode freight rates of 30 percent over the expected average costs every three years. [Ref. 21]

D. RESULTS

Table 9.1 indicates the Average Net Present Values (in US$) for the two scenarios, with the two alternatives, standard deviation (sigma) of 20 and 30 percent, respectively. Appendices F and G include the simulation outputs which provided the expected number of parts to be shipped for repairing.

MODE	YEAR											NPV
	0	1	2	3	4	5	6	7	8	9	10	
Sea mode sigma=20 %	2237710	29147	29497	29851	30209	33629	30938	31309	31685	32066	35695	**$2,469,591.57**
Sea mode sigma=30 %	2237710	29147	29497	29851	30209	33629	30938	31309	31685	32066	35695	**$2,469,591.57**
Air mode sigma=20 %	949244	80070	82472	110430	87372	89810	119922	94686	97124	129431	102000	**$1,619,519.81**
Air mode sigma=30 %	949244	80070	82472	110430	87372	89810	119922	94686	97124	129431	102000	**$1,619,519.81**

Table 9.1. Average Net Present Values (US$).

Note that the total acquisition costs[1] are displayed in year zero, while average transportation costs[2] per year are displayed in years one to ten. No changes in average NPV were observed when changing standard deviations for the same transportation mode. From the last column of Table 9.1 (NPV), we conclude that using air mode instead of sea mode will result in 34.42 percent of savings in total cost.

[1] Total acquisition cost for the sea mode was calculated using costs provided in Table 8.1 and the expected number of parts to be shipped for repairing provided in the Appendix F, while for air mode we used Table 8.1 and information from Appendix G.

[2] Transportation cost for the sea mode was estimated on container space availability basis (weekly shipments) and using the expected number of parts to be shipped for repairing provided in the Appendix F, while for air mode we used Table 6.2 and information from Appendix G.

Figures 9.1 to 9.4 forecast the range of variability of the NPV for the two scenarios/two alternatives, with a confidence interval of 100 percent. These graphs are very useful for assessing the risks, and they are the typical outputs from Crystal Ball.

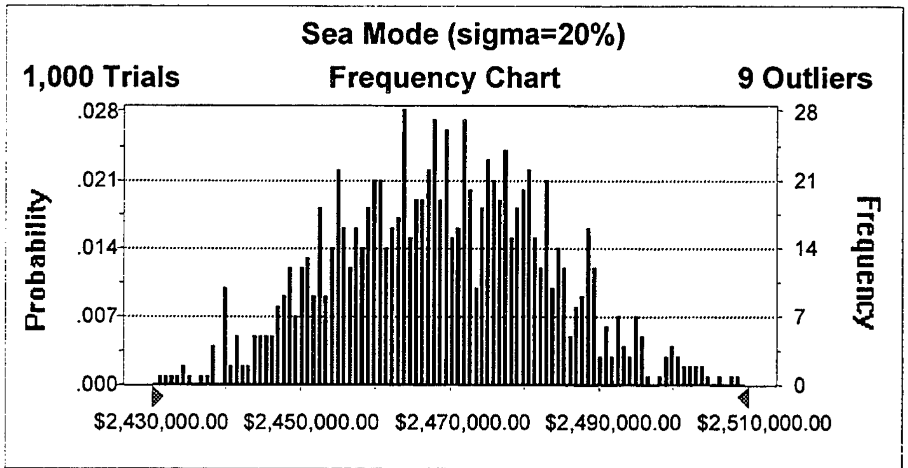


Figure 9.1. Sea Mode (sigma=20%) – Frequency Chart.

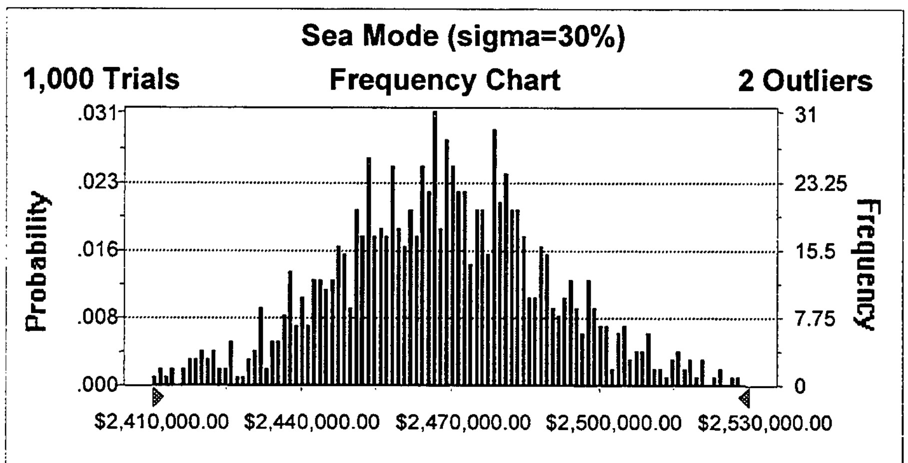


Figure 9.2. Sea Mode (sigma=30%) – Frequency Chart.

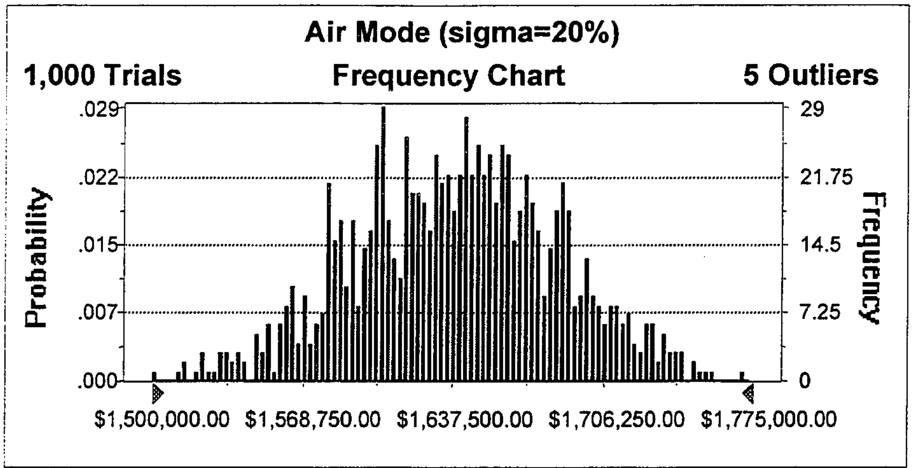


Figure 9.3. Air Mode (sigma=20%) – Frequency Chart.

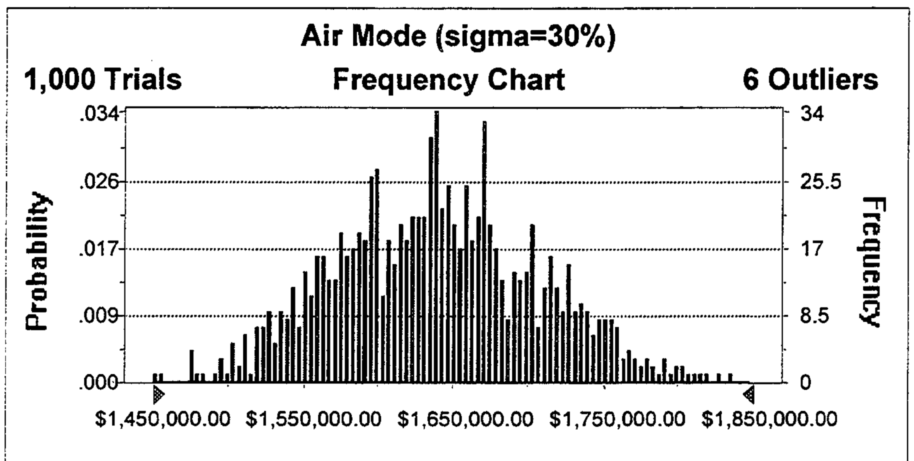


Figure 9.4. Air Mode (sigma=30%) – Frequency Chart.

Now, we obtain a single graph (see Figure 9.5) by overlaying the variability ranges for both transportation modes with sigma equals thirty percent.

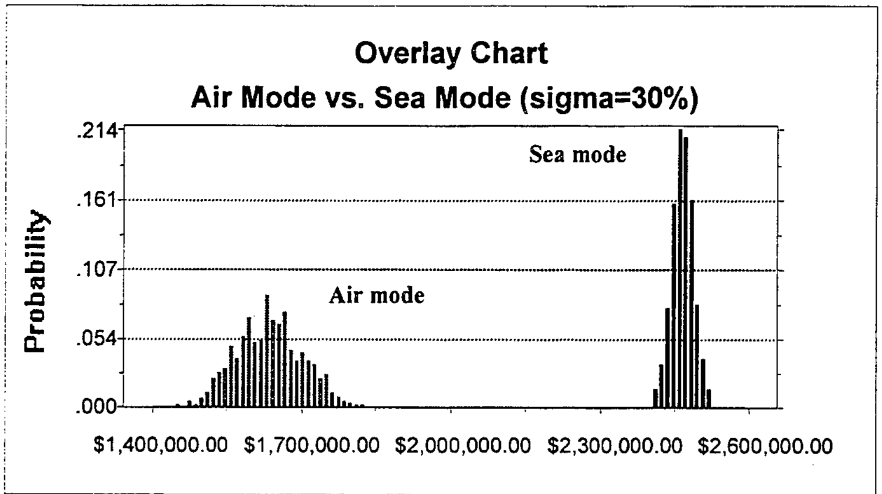


Figure 9.5. Overlay Chart – Air Mode vs. Sea Mode (sigma=30%).

This comparison makes obvious the advantage of choosing air mode over sea mode. For example, by comparing the more pessimistic situation for air mode transportation (US$1,850,000.00) to the more optimistic one for sea mode (US$2,410,000.00) the results still ensure 23.24 percent in savings of the total cost, while A_0 remains unaltered.

E. CHAPTER SUMMARY

In this chapter, we calculated the net present values of two different scenarios: one with current transportation time (sea mode) and current inventory levels, and a second one with reduced transportation time (air mode) and reduced inventory in such a manner that the resulting A_0 was the same for both scenarios, thus making them fairly comparable. We performed a sensitivity analysis using a Monte Carlo simulation to assess the risks of decision making. The results demonstrated the advantage of choosing air mode transportation over sea mode in terms of cost-effectiveness.

Chapter X will present the main conclusions derived from the analyses performed in this and previous chapters. It will also provide some recommendations regarding an

effective management model to improve the readiness of the A-4 aircraft fleet for the Argentine Air Force and the Brazilian Navy.

X. CONCLUSIONS AND RECOMMENDATIONS

A. INTRODUCTION

The previous chapters have developed a trade-off assessment between inventory management and fleet readiness concerning the Argentine Air Force and the Brazilian Navy A-4 aircraft fleets. The interdependent logistics decisions of inventory and transportation for their repairable-item inventory systems were investigated.

This final chapter presents our conclusions and recommendations for the improvement of the operational availability of their A-4 fleets, as well as for the inventory management of their systems.

B. CONCLUSIONS

The presented methodology, which combines a set of techniques such as simulation modeling, multiple regression analysis, linear programming and Monte Carlo simulation, is an effective managerial tool to be used by logisticians when dealing with decisions related to operational availability and inventory vs. total cycle time trade-off. This valuable tool can be easily adjusted for use with other military repairable-item inventory systems. However, we are aware about the necessity of changing the educational requirements of our logisticians in order to take full advantage of such methodology. Eaton [Ref. 22] well summarized this connection:

> Weapon systems are more complex, logistics support systems are more complex, and team communications are more complex. Moreover, decisions at all levels have become more complex and mistakes are more costly than ever.

We urgently need balanced viewpoints in the value-net working trade-off decisions. Specifically logisticians must be able to understand systems functional analysis: functional allocation, reliability allocation, complexity analysis, cost analysis and so on. In addition they must be adroit in modeling and simulations for logistics decision support.

We now present the conclusions of this study.

- A consolidation of the Brazilian Navy and the Argentine Air Force aviation electronic component inventories will benefit both Armed Forces in terms of higher operational availability for their fleets. From a current scenario where the Brazilian Navy and the Argentine Air Force A-4 fleets are achieving operational availability of 83.98 and 86.59 percent, respectively, an improvement will result from consolidating inventories. The resulting A_0 is 88.84 percent for the coalition model and it represents on average an increase of 0.973[1] A-4 aircraft will be fully mission capable over a period of ten years for the Brazilian Navy, while the Argentines benefit from an increase of 0.678[2].

- Reducing transportation time by changing from sea mode to air mode will increase the operational availability of the A4 fleets by approximately seven percent for the coalition model (see Chapter VI). This represents having an average of 3.5[3] more A-4s fully mission capable over a period of 10 years, without the need for increasing inventory levels.

- The metamodel equation, developed in Chapter VII, showed which LRUs/SRUs that make the highest and lowest contribution to A_0. The Inertial Navigation Unit (LRU_4) and the Air Data Computer (LRU_3) made the highest contributions, while the Torque Drive Power Supply Module (SRU_2), the lowest. The metamodel also demonstrated that by reducing transportation time to four days (expedited air mode) from an average of 26 days for sea mode transportation, it is possible to achieve 75 percent of operational availability with zero spare parts inventory.

- Operational availability can be increased by adding spare parts to the rotable pools, but this increase follows a diminishing rate until the point where A_0

[1] The value of 0.973 was calculated by multiplying the number of Brazilian A-4 aircraft by the difference between A_0 achieved after and before the coalition model. Thus, 0.973=20*(0.88838–0.83975).

[2] The value of 0.678 was calculated by multiplying the number of Argentine A-4 aircraft by the difference between A_0 achieved after and before the coalition model. Thus, 0.678=30*(0.88838–0.86578).

[3] The value of 3.5 was calculated by multiplying the total number of aircraft (coalition model) by the difference between A_0 achieved after and before reducing transportation time. Thus, 3.5=50*(0.95034–0.88838).

stabilizes. From this point, there is no contribution and A_0 remains unaltered. This is counter to many common managerial practices such as expecting A_0 to increase by increasing inventory indefinitely.

- A concept of material quickness vs. quantity was highlighted which advocates that using a rapid and responsive shipping mode, such as air mode, reduces the volume of spare items required in the system inventory to achieve a specific A_0. In our study, the transportation time reduction generates savings in the 23 to 43 percent range in total cost over a 10-year period. These savings were calculated by including freight rate fluctuations. Although the air mode cost for an LRU/SRU is more expensive than the sea mode cost, this additional expense is offset by the reduction in system inventory costs, thereby reducing the total system cost.

C. RECOMMENDATIONS

The lessons learned from the extensive analyses conducted in this thesis support the following recommendations:

- Taking advantage of the extraordinary political times that Brazil and Argentina are enjoying in terms of an integration process, a collaborative inventory management of their A-4 fleets should be analyzed and implemented. This will bring economical and operational advantages to both Armed Forces.

- We strongly recommend the reduction in transportation cycle time by changing from sea mode to air mode as the way of shipping aviation electronic components to manufacturers in the United States for depot level maintenance.

- The use of the methodology presented in this thesis should be promoted in both Armed Forces as a way to provide an effective managerial resource for long-term decision making to improve the readiness of aircraft fleet, while optimizing the use of scarce resources.

- Critical components must be closely tracked and have their related data accurately recorded. Historical data collection of Mean Time Between Failures, Mean Time To Repair and so on, become fundamental at the time of using methodologies such as the one presented in this paper. We encountered a lack of information during our data collection process from the Argentine Air Force and the Brazilian Navy. Different explanations were given such as information not available at the time of the A-4 aircraft acquisition, lack of resources, poor managerial tools and organizational cultural reasons.

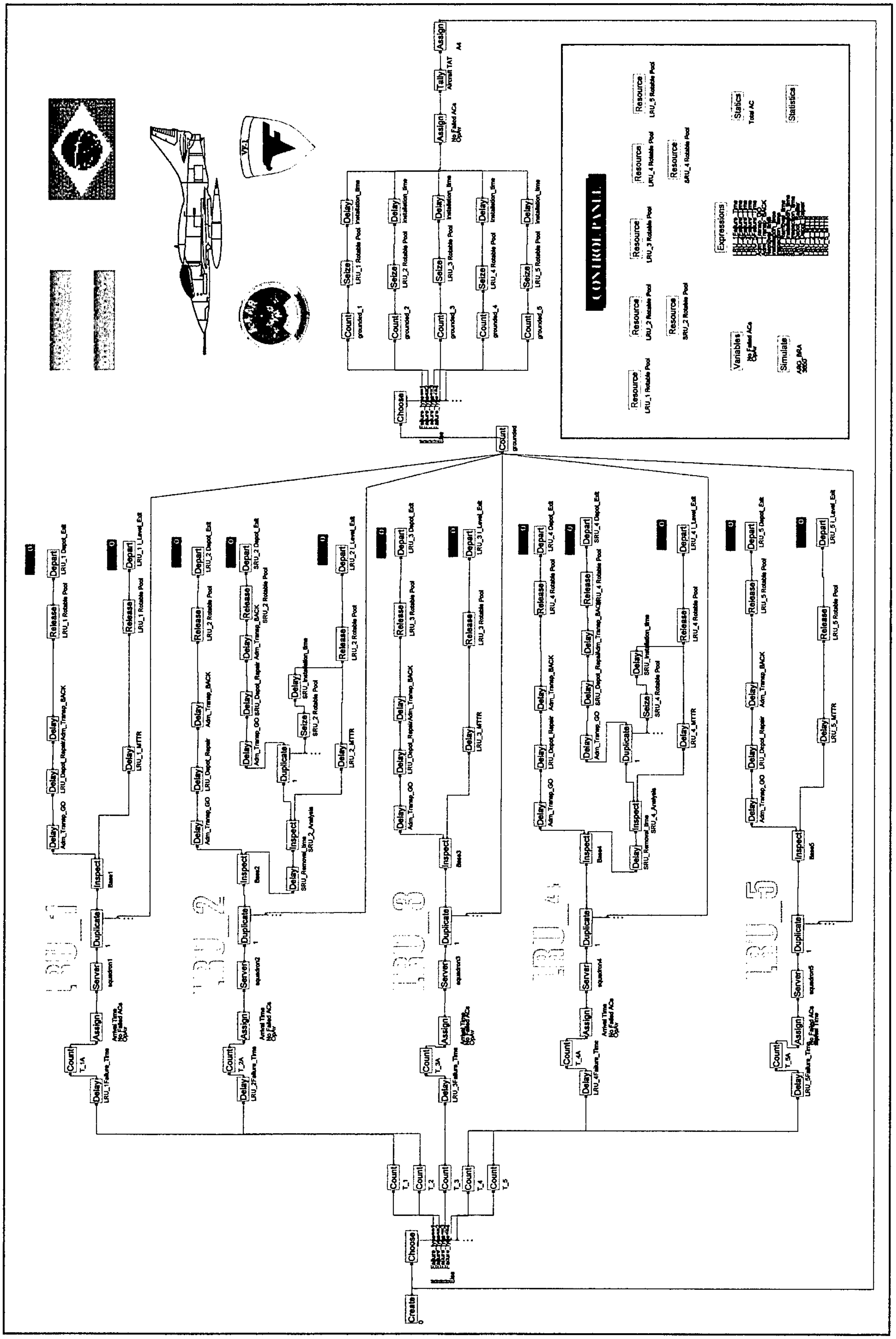
- Both Armed Forced should be aware of the necessity of introducing cultural changes to eradicate inappropriate managerial practices such as the one that looks for increasing inventory levels indefinitely while expecting A_0 to increase.
- A change in the educational requirements of our logisticians should be considered. The new weapon systems and the complexity associated with them, as well as with the complex logistics support required are strong reasons to be concerned with the logisticians' educational background.
- We suggest further studies to analyze the implementation of total asset visibility between the Brazilian Navy and the Argentine Air Force inventory systems, and the possibilities to standardize critical components for both the A-4 aircraft fleets to make the inventory consolidation more effective.
- Advantages of joint contracting policies for acquisition, repairing, and shipping of aircraft components are also recommended for future research.

D. SUMMARY

The initial chapters were devoted to the introduction of the concept of military repairable-item inventory systems. We then developed a simulation model to mimic the repair process of a selected group of Brazilian and Argentine A-4 critical electronic components. A coalition model was proposed and the fleets' operational availability was enhanced as a consequence of consolidating inventories. We also evaluated the impact of inventory level variation and transportation time reduction on the operational availability. A cost-effectiveness analyzes was performed.

This thesis showed that the best combination for the Brazilian Navy and the Argentine Air Force repairable-item inventory system is to consolidate inventories of the critical components considered in this study under a coalition model, and use air mode transportation for shipping them abroad for repair. This combination leads to the lowest average total system cost for an operational availability of 88.84 percent over a period of 10 years.

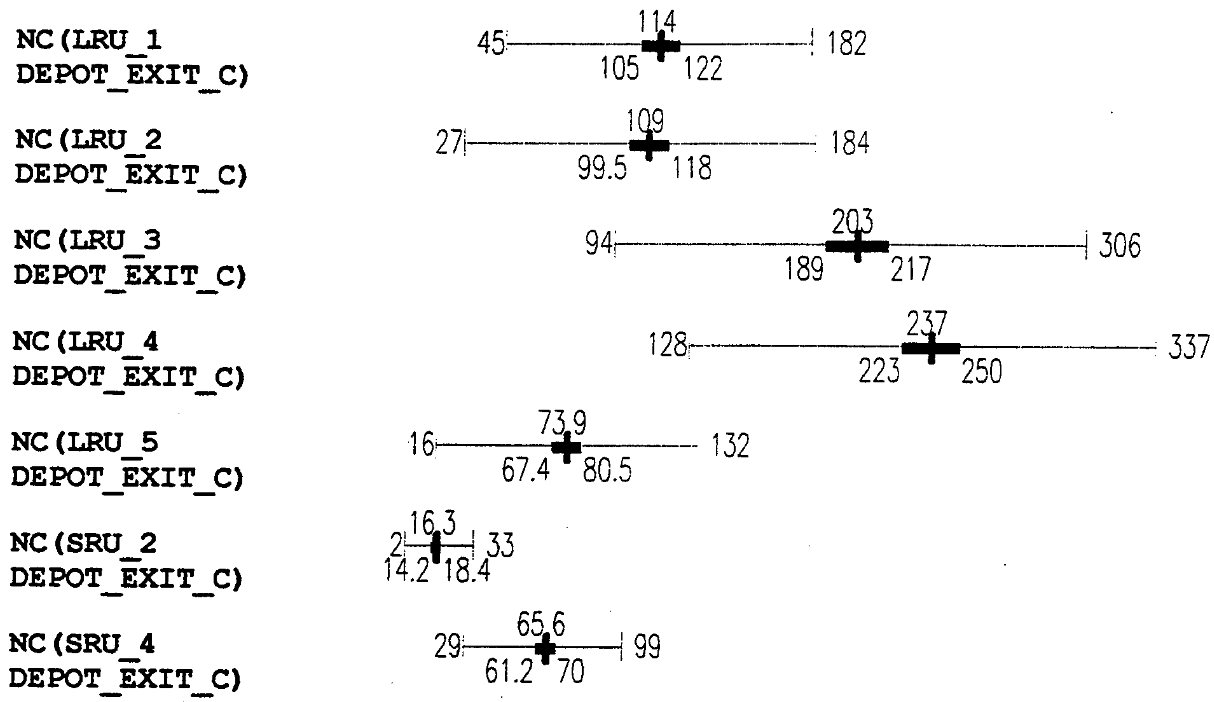
APPENDIX A. SIMULATION MODEL


CONTROL PANEL
LRU_1
LRU_2
LRU_3
LRU_4
LRU_5

APPENDIX B. SIMULATION OUTPUT – COALITION MODEL (AIR MODE, CURRENT INVENTORY LEVELS)

Observation Intervals

Avg
Min — Max
95% CL



Output Summary for 50 Replications

Project: ARG_BRA (REDUCED TIME) Run
execution date : 10/30/1999
Analyst: M_M Model revision date:
10/30/1999

OUTPUTS

Identifier	Average	Half-width	Minimum	Maximum	# Replications
NC(LRU_4 DEPOT_EXIT_C)	236.68	13.396	128.00	337.00	50
NC(LRU_2 DEPOT_EXIT_C)	108.72	9.2993	27.000	184.00	50
DAVG(OPERATIONAL AVAIL	.95034	.00336	.91901	.96878	50
NC(LRU_5 DEPOT_EXIT_C)	73.940	6.6336	16.000	132.00	50
NC(LRU_3 DEPOT_EXIT_C)	203.02	14.083	94.000	306.00	50
NC(LRU_1 DEPOT_EXIT_C)	113.54	8.9765	45.000	182.00	50
NC(SRU_4 DEPOT_EXIT_C)	65.560	4.4460	29.000	99.000	50
NC(SRU_2 DEPOT_EXIT_C)	16.300	2.0970	2.0000	33.000	50

Simulation run time: 19.20 minutes.
Simulation run complete.

APPENDIX C. TABLE OF SIMULATIONS RUNS (128 RUNS, 50 REPLICATIONS EACH RUN)

Run	LRU_1	LRU_2	LRU_3	LRU_4	LRU_5	SRU_2	SRU_4	Average Ao
1	1	1	1	1	1	1	1	0.79211
2	1	1	1	1	1	1	10	0.80172
3	1	1	1	1	1	10	1	0.79324
4	1	1	1	1	1	10	10	0.80134
5	1	1	1	1	5	1	1	0.80919
6	1	1	1	1	5	1	10	0.81620
7	1	1	1	1	5	10	1	0.80642
8	1	1	1	1	5	10	10	0.81667
9	1	1	1	5	1	1	1	0.83620
10	1	1	1	5	1	1	10	0.84501
11	1	1	1	5	1	10	1	0.84038
12	1	1	1	5	1	10	10	0.84687
13	1	1	1	5	5	1	1	0.85504
14	1	1	1	5	5	1	10	0.86007
15	1	1	1	5	5	10	1	0.85471
16	1	1	1	5	5	10	10	0.85935
17	1	1	5	1	1	1	1	0.83392
18	1	1	5	1	1	1	10	0.84205
19	1	1	5	1	1	10	1	0.83535
20	1	1	5	1	1	10	10	0.83971
21	1	1	5	1	5	1	1	0.85113
22	1	1	5	1	5	1	10	0.85407
23	1	1	5	1	5	10	1	0.84961
24	1	1	5	1	5	10	10	0.85607
25	1	1	5	5	1	1	1	0.88062
26	1	1	5	5	1	1	10	0.88514
27	1	1	5	5	1	10	1	0.88095
28	1	1	5	5	1	10	10	0.88809
29	1	1	5	5	5	1	1	0.89592
30	1	1	5	5	5	1	10	0.90355
31	1	1	5	5	5	10	1	0.89674
32	1	1	5	5	5	10	10	0.90456
33	1	5	1	1	1	1	1	0.81891
34	1	5	1	1	1	1	10	0.82161
35	1	5	1	1	1	10	1	0.81592
36	1	5	1	1	1	10	10	0.81920
37	1	5	1	1	5	1	1	0.83258
38	1	5	1	1	5	1	10	0.83844
39	1	5	1	1	5	10	1	0.83660
40	1	5	1	1	5	10	10	0.83601
41	1	5	1	5	1	1	1	0.85987
42	1	5	1	5	1	1	10	0.86627

Run	LRU_1	LRU_2	LRU_3	LRU_4	LRU_5	SRU_2	SRU_4	Average Ao
43	1	5	1	5	1	10	1	0.86154
44	1	5	1	5	1	10	10	0.86791
45	1	5	1	5	5	1	1	0.88201
46	1	5	1	5	5	1	10	0.88427
47	1	5	1	5	5	10	1	0.87917
48	1	5	1	5	5	10	10	0.88618
49	1	5	5	1	1	1	1	0.85697
50	1	5	5	1	1	1	10	0.86295
51	1	5	5	1	1	10	1	0.85739
52	1	5	5	1	1	10	10	0.86508
53	1	5	5	1	5	1	1	0.87547
54	1	5	5	1	5	1	10	0.88371
55	1	5	5	1	5	10	1	0.87232
56	1	5	5	1	5	10	10	0.88520
57	1	5	5	5	1	1	1	0.90388
58	1	5	5	5	1	1	10	0.91047
59	1	5	5	5	1	10	1	0.90029
60	1	5	5	5	1	10	10	0.90618
61	1	5	5	5	5	1	1	0.91447
62	1	5	5	5	5	1	10	0.92347
63	1	5	5	5	5	10	1	0.91984
64	1	5	5	5	5	10	10	0.92079
65	5	1	1	1	1	1	1	0.81906
66	5	1	1	1	1	1	10	0.82511
67	5	1	1	1	1	10	1	0.81864
68	5	1	1	1	1	10	10	0.82562
69	5	1	1	1	5	1	1	0.83092
70	5	1	1	1	5	1	10	0.84356
71	5	1	1	1	5	10	1	0.83882
72	5	1	1	1	5	10	10	0.84512
73	5	1	1	5	1	1	1	0.86659
74	5	1	1	5	1	1	10	0.86781
75	5	1	1	5	1	10	1	0.86122
76	5	1	1	5	1	10	10	0.87272
77	5	1	1	5	5	1	1	0.87452
78	5	1	1	5	5	1	10	0.89068
79	5	1	1	5	5	10	1	0.87629
80	5	1	1	5	5	10	10	0.88748
81	5	1	5	1	1	1	1	0.85956
82	5	1	5	1	1	1	10	0.86961
83	5	1	5	1	1	10	1	0.86346
84	5	1	5	1	1	10	10	0.86931
85	5	1	5	1	5	1	1	0.87789

Run	LRU_1	LRU_2	LRU_3	LRU_4	LRU_5	SRU_2	SRU_4	Average Ao
86	5	1	5	1	5	1	10	0.88214
87	5	1	5	1	5	10	1	0.87430
88	5	1	5	1	5	10	10	0.88159
89	5	1	5	5	1	1	1	0.90716
90	5	1	5	5	1	1	10	0.91086
91	5	1	5	5	1	10	1	0.90641
92	5	1	5	5	1	10	10	0.91404
93	5	1	5	5	5	1	1	0.91886
94	5	1	5	5	5	1	10	0.92817
95	5	1	5	5	5	10	1	0.92123
96	5	1	5	5	5	10	10	0.92915
97	5	5	1	1	1	1	1	0.84587
98	5	5	1	1	1	1	10	0.84309
99	5	5	1	1	1	10	1	0.84161
100	5	5	1	1	1	10	10	0.85074
101	5	5	1	1	5	1	1	0.86059
102	5	5	1	1	5	1	10	0.86089
103	5	5	1	1	5	10	1	0.85582
104	5	5	1	1	5	10	10	0.86606
105	5	5	1	5	1	1	1	0.88851
106	5	5	1	5	1	1	10	0.89394
107	5	5	1	5	1	10	1	0.88627
108	5	5	1	5	1	10	10	0.89403
109	5	5	1	5	5	1	1	0.89762
110	5	5	1	5	5	1	10	0.91098
111	5	5	1	5	5	10	1	0.90345
112	5	5	1	5	5	10	10	0.91153
113	5	5	5	1	1	1	1	0.88445
114	5	5	5	1	1	1	10	0.89048
115	5	5	5	1	1	10	1	0.88323
116	5	5	5	1	1	10	10	0.88863
117	5	5	5	1	5	1	1	0.89723
118	5	5	5	1	5	1	10	0.90680
119	5	5	5	1	5	10	1	0.89982
120	5	5	5	1	5	10	10	0.90745
121	5	5	5	5	1	1	1	0.92675
122	5	5	5	5	1	1	10	0.93251
123	5	5	5	5	1	10	1	0.92825
124	5	5	5	5	1	10	10	0.93336
125	5	5	5	5	5	1	1	0.94359
126	5	5	5	5	5	1	10	0.95057
127	5	5	5	5	5	10	1	0.94235
128	5	5	5	5	5	10	10	0.95034

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APPENDIX D. MULTIPLE REGRESSION ANALYSIS – SUMMARY OUTPUT

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.998281899
R Square	0.99656675
Adjusted R Sqı	0.996366477
Standard Error	0.002179437
Observations	128

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	7	0.165451517	0.023636	4976.044	1.2405E-144
Residual	120	0.000569993	4.75E-06		
Total	127	0.166021511			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.755122092	0.000751966	1004.197	2.5E-237	0.753633252	0.756611	0.753633252	0.756610932
X Variable 1	0.006397422	9.63184E-05	66.41952	1.75E-96	0.006206718	0.006588	0.006206718	0.006588125
X Variable 2	0.005671406	9.63184E-05	58.88186	2.16E-90	0.005480703	0.005862	0.005480703	0.00586211
X Variable 3	0.010309922	9.63184E-05	107.04	6.3E-121	0.010119218	0.010501	0.010119218	0.010500625
X Variable 4	0.011181328	9.63184E-05	116.0871	4.1E-125	0.010990625	0.011372	0.010990625	0.011372032
X Variable 5	0.003982812	9.63184E-05	41.35048	7.62E-73	0.003792109	0.004174	0.003792109	0.004173516
X Variable 6	4.22917E-05	4.28082E-05	0.987934	0.325173	-4.24655E-05	0.000127	-4.24655E-05	0.000127049
X Variable 7	0.000752569	4.28082E-05	17.58004	5.39E-35	0.000667812	0.000837	0.000667812	0.000837327

APPENDIX E. LINEAR PROGRAMMING SOLUTION

Microsoft Excel 8.0a Answer Report
Worksheet: [SOLVERTHESISreducedtime.xls]Sheet1
Report Created: 10/22/99 10:04:01 AM

Target Cell (Min)

Cell	Name	Original Value	Final Value
$A$4	OBJECTIVE FUNCTION	961409.0555	961409.0555

Adjustable Cells

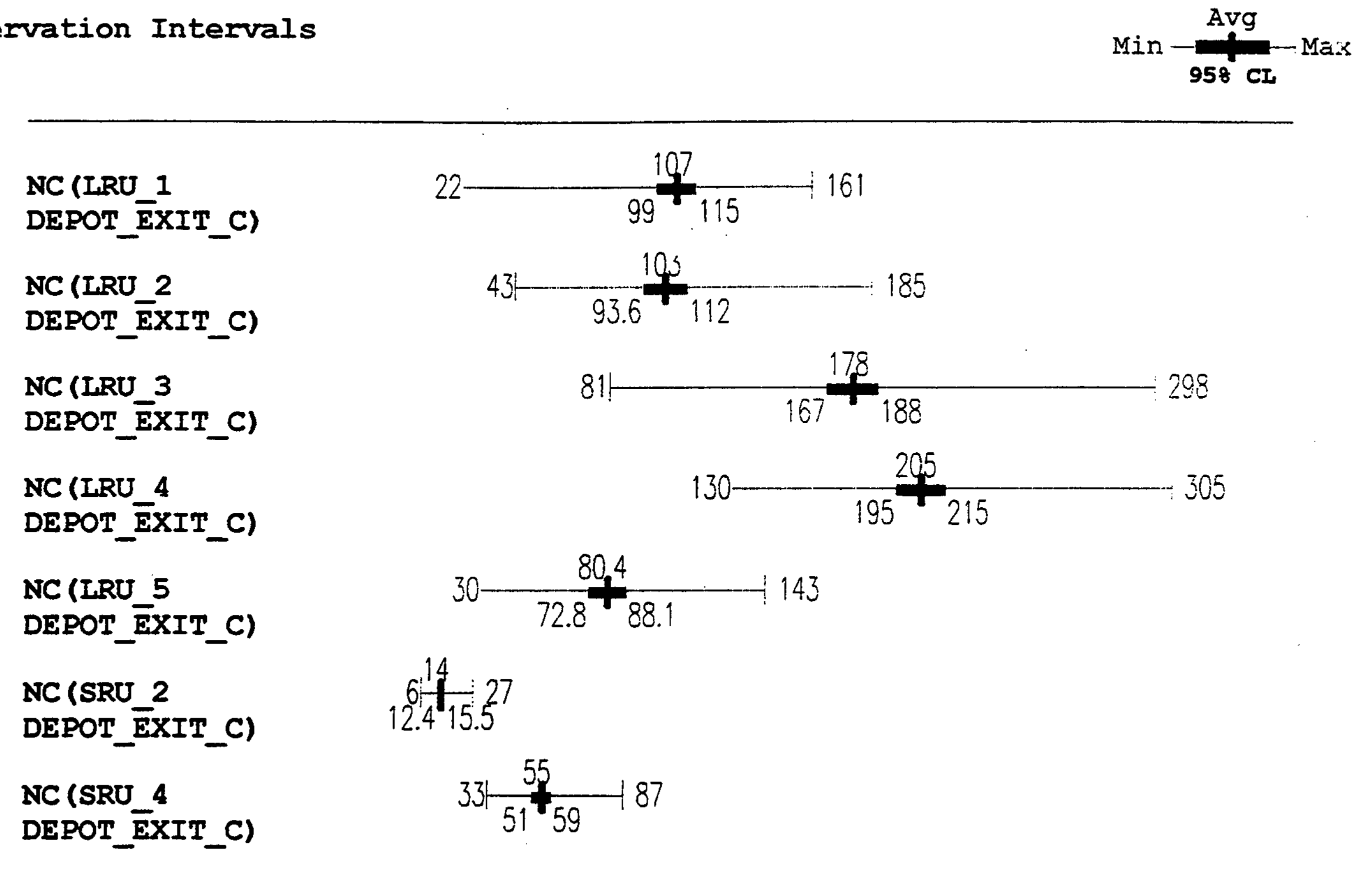
Cell	Name	Original Value	Final Value
$C$4	LRU1 VARIABLES/SOLUTION	1	1
$C$5	LRU2 VARIABLES/SOLUTION	5	5
$C$6	LRU3 VARIABLES/SOLUTION	5	5
$C$7	LRU4 VARIABLES/SOLUTION	3.155513652	3.155513652
$C$8	LRU5 VARIABLES/SOLUTION	1	1
$C$9	SRU2 VARIABLES/SOLUTION	1	1
$C$10	SRU4 VARIABLES/SOLUTION	10	10

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$D$4	LRU1 CONSTRAINTS	0.132900001	$D$4=$E$4	Not Binding	0
$D$5	LRU2 CONSTRAINTS	1	$D$5>=$E$5	Binding	0
$D$6	LRU3 CONSTRAINTS	5	$D$6>=$E$6	Not Binding	4
$D$7	LRU4 CONSTRAINTS	5	$D$7>=$E$7	Not Binding	4
$D$8	LRU5 CONSTRAINTS	3.155513652	$D$8>=$E$8	Not Binding	2.155513652
$D$9	SRU2 CONSTRAINTS	1	$D$9>=$E$9	Binding	0
$D$10	SRU4 CONSTRAINTS	1	$D$10<=$E$10	Not Binding	4
$D$11	CONSTRAINTS	5	$D$11<=$E$11	Binding	0
$D$12	CONSTRAINTS	5	$D$12<=$E$12	Binding	0
$D$13	CONSTRAINTS	3.155513652	$D$13<=$E$13	Not Binding	1.844486348
$D$14	CONSTRAINTS	1	$D$14<=$E$14	Not Binding	4
$D$15	CONSTRAINTS	1	$D$15<=$E$15	Not Binding	9
$D$16	CONSTRAINTS	10	$D$16<=$E$16	Binding	0
$D$17	CONSTRAINTS	1	$D$17>=$E$17	Binding	0
$D$18	CONSTRAINTS	10	$D$18>=$E$18	Not Binding	9

APPENDIX F. SIMULATION OUTPUT – COALITION MODEL (SEA MODE, CURRENT INVENTORY LEVELS)

Observation Intervals



Output Summary for 50 Replications

Project: ARG_BRA (50 ACFT; LRUs=5,5,5,5,5; SRUs=10,10)
Run execution date : 10/18/1999
Analyst: M_M Model revision date: 10/18/1999

OUTPUTS

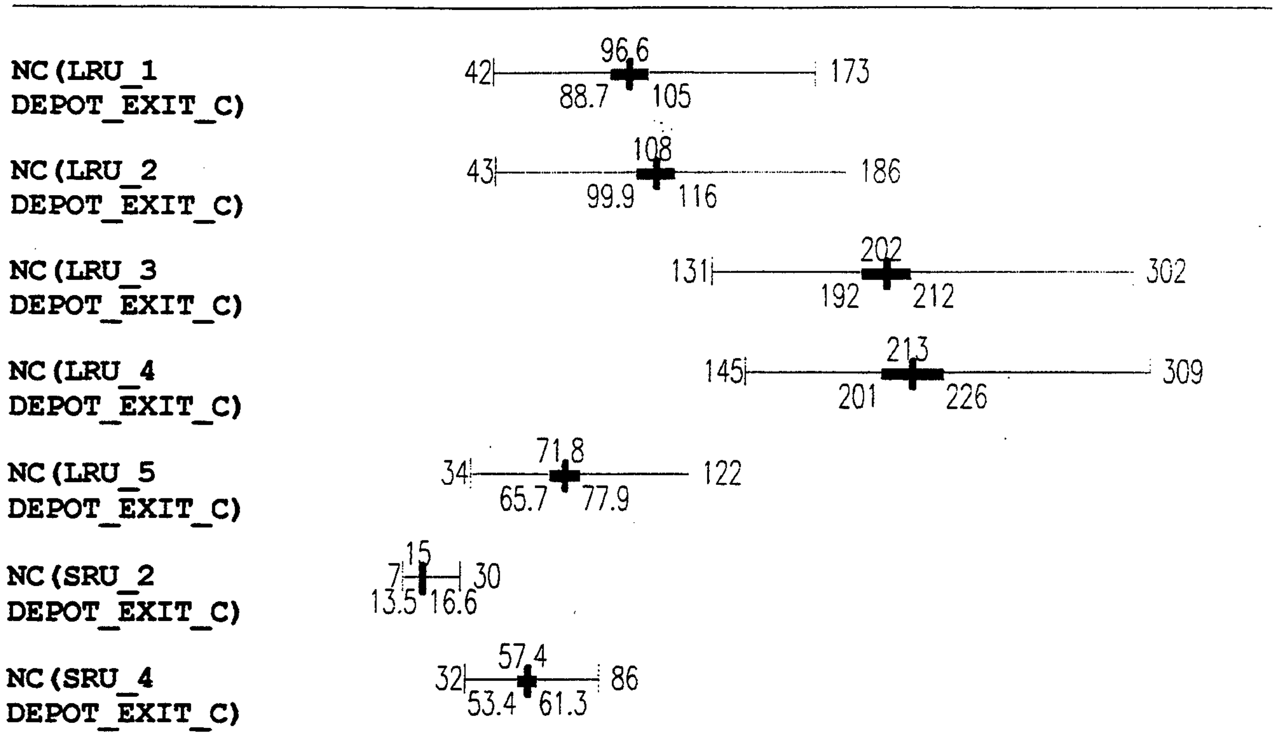
Identifier	Average	Half-width	Minimum	Maximum	# Replications
NC(LRU_4 DEPOT_EXIT_C)	205.12	10.167	130.00	305.00	50
NC(LRU_2 DEPOT_EXIT_C)	102.58	9.0299	43.000	185.00	50
DAVG(OPERATIONAL AVAIL	.88838	.00470	.83537	.91855	50
NC(LRU_5 DEPOT_EXIT_C)	80.440	7.7029	30.000	143.00	50
NC(LRU_3 DEPOT_EXIT_C)	177.72	10.499	81.000	298.00	50
NC(LRU_1 DEPOT_EXIT_C)	106.84	7.9589	22.000	161.00	50
NC(SRU_4 DEPOT_EXIT_C)	55.020	4.0398	33.000	87.000	50
NC(SRU_2 DEPOT_EXIT_C)	13.980	1.5579	6.0000	27.000	50

Simulation run time: 17.87 minutes.
Simulation run complete.

APPENDIX G. SIMULATION OUTPUT – COALITION MODEL (AIR MODE, REDUCED INVENTORY LEVELS)

Observation Intervals

Avg
Min Max
95% CL




```
Output Summary for 50 Replications

Project:  ARG_BRA (reduced transp. Time; LRUS=1,5,5,3,1;SRUs=1,10)
Run execution date :  10/22/1999
Analyst:  M_M                              Model revision date:
10/22/1999
```

OUTPUTS

Identifier	Average	Half-width	Minimum	Maximum	# Replications
NC(LRU_4 DEPOT_EXIT_C)	213.14	12.735	145.00	309.00	50
NC(LRU_2 DEPOT_EXIT_C)	107.82	7.9999	43.000	186.00	50
DAVG(OPERATIONAL AVAIL	.89206	.00332	.86392	.91178	50
NC(LRU_5 DEPOT_EXIT_C)	71.800	6.1238	34.000	122.00	50
NC(LRU_3 DEPOT_EXIT_C)	202.34	10.052	131.00	302.00	50
NC(LRU_1 DEPOT_EXIT_C)	96.620	7.9696	42.000	173.00	50
NC(SRU_4 DEPOT_EXIT_C)	57.360	3.9905	32.000	86.000	50
NC(SRU_2 DEPOT_EXIT_C)	15.020	1.5804	7.0000	30.000	50

Simulation run time: 16.45 minutes.
Simulation run complete.

LIST OF REFERENCES

1. Interviews with Mr. Shawn Delaware, Fleet Support Team Leader, Naval Aviation Depot, North Island, San Diego, CA.

2. Kacowicz, Arie M., Stable Peace in South America, July 1999.

3. <Mercosur> <Website> <http://www.americasnet.com/mauritz/mercosur> (Accessed <8/15/99>).

4. <La Nacion> <Website> <http://www.lanacion.com.ar> (Accessed <8/15/99>).

5. Grandi, Jorge. "La integración, la cooperación argentino-brasilera y la disuasión nuclear desarmada." *America Latina/Internacional* 3(10): 70-4. CARI. 1992. *El Rol de las Fuerzas Armadas en el Mercosur.* Buenos Aires. Consejo Argentino para las Relaciones Internacionales (CARI)/Fundación Konrad Adenauer, 1986.

6. Cavagnari Filho, Geraldo Lesbat, "Brasil-Argentina: Autonomia Estratégica y Cooperación Militar." In *Argentina-Brasil:Perspectivas Comparativas Ejes de Integración.* Mónica Hirst, ed. Buenos Aires. Editorial Tesis/Facultad Latinoamericana de Ciencias Sociales, 1990.

7. Barletta, Michael, Democratic Security and Diversionary Peace: Nuclear Confidence-Building in Argentina and Brazil-September 1998.

8. <La Nacion> <Website> <http://www.lanacion.com.ar> (Accessed <8/21/99>).

9. <Ambito Financiero> <Website> http://www.ambitofinanciero.com> (Accessed<11/04/99>).

10. Blanchard, Benjamin S., *Logistics Engineering and Management*, Fifth Edition, Prentice Hall, Inc., 1998.

11. <Hunting Engineering><Website> <http://www.hunting-engineering.co.uk>(Accessed<10/29/99>).

12. < Systems Modeling><Website> <http://www.sm.com/releases/default.htm>(Accessed<11/04/99>).

13. Kelton, W. D., R. P. Sadowski, and D. A. Sadowski, *Simulation with Arena*, McGraw-Hill, 1998.

14. Hoop, Wallace J. and Mark L. Spearman, *Factory Physics*, "Foundations of Manufacturing Management".

15. Barton, Russell R., Simulation Metamodels, Department of Industrial and Manufacturing Engineering, The Pennsylvania State University, University Park, PA 16082 U.S.A..

16. Kleijnen, J. P. C., "Regression Metamodels for Simulation with Common Random Numbers: Comparison of Validation Tests and Confidence Intervals," *Management Science*, vol. 38, no.8, pp. 1164-1185, August 1992.

17. Levine, David M., Mark L. Berenson, and David Stephan, *Statistics for Managers Using Microsoft Excel*, Prentice Hall, 1998.

18. Greenberg, Boardman and Vining Weimer, *Cost-Benefit Analysis, Concept and Practice*, Prentice Hall, 1996.

19. Render; Barry and Ralph M. Stair Jr., *Quantitative Analysis for Management*, Sixth Edition-Prentice Hall, 1997.

20. *Crystal Ball-* Version 4.0-User Manual.

21. Purchasing Online- "The magazine of total supply chain management", Dec-10-1992 and March 20-1997 http://www.manufacturing.net/magazine/pur...ing/archives/1997/pur0320.97/032tnews.htm (accessed Nov 1999).

22. RADM (Ret.) Donald R. Eaton, A New Strategy: Cultural Change For Better Logistics by the 21st Century (Handout as Guest Lecturer), 1999.

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